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IMPROVED SELF-CONTAINED BREATHING APPARATUS CONCEPT

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→ demonstrated that the prototype SCBA meets all performance requirements, except for weight. The fully charged prototype weighs 34 pounds, the maximum acceptable weight is 30 pounds. With the other performance requirements either met or exceeded, manned testing of the SCBA can proceed. ←

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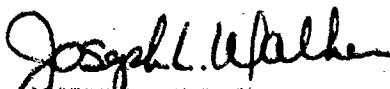


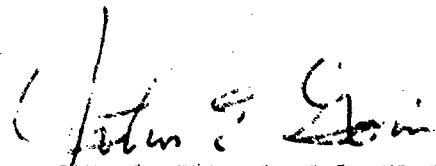
PREFACE

This report was prepared by Electronic Data Systems Corporation, 1607D Lisenby Avenue, Panama City, Florida 32401, under contract F08635-80-C-0297 with the Air Force Engineering and Services Center, Tyndall Air Force Base, Florida 32403. The work was begun on 2 October 1980 and completed on 18 June 1982.

This report has been reviewed by the Public Affairs Office (PA) and is releasable to the National Technical Information Service (NTIS). At NTIS it will be available to the general public, including foreign nationals.

This technical report has been reviewed and is approved for publication.


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TABLE OF CONTENTS

SECTION	TITLE	PAGE
I	INTRODUCTION.	1
	1. Objective	1
	a. General	1
	b. Scope	1
	c. Technical Requirements	2
	2. Background	3
	3. General Description	4
	a. Physical Characteristics Summary	4
	b. Operation	6
	4. Unmanned Test and Evaluation Summary	6
	5. Conclusions/Recommendations	7
	a. Conclusions.	7
	b. Recommendations	9
II	TECHNICAL DESCRIPTION	11
	1. Design Descriptions	11
	a. General System Description	11
	b. Subsystem Design	20
	2. Design Analysis	39
	a. Fundamental Relationships	39
	b. Determination of Transition from Push-through to Pull-through	39
	c. PO_2 Performance in a Pull-through Mode	47
	d. PO_2 Performance in a Push-through Mode	49
	e. CO_2 Absorbent Canister Design.	51
	f. Coolant Canister Design.	56

TABLE OF CONTENTS (CONCLUDED)

SECTION	TITLE	PAGE
II	g. Gas Supply Requirements	57
	h. Materials and Weight.	60
	i. Pressure Drop Computer Modeling	63
	j. Engineering Drawings.	71
	3. Basic Operational Procedure.	73
	a. Controls and Displays	73
	b. Checkout.	75
	c. Donning the SCBA.	75
	d. Operation	77
	e. Turnaround Procedures	79
III	UNMANNED TEST PROGRAM	87
	1. Requirements	87
	a. Breathing Resistance.	87
	b. First Stage Regulator	97
	c. Supply Gas Flow Rate.	97
	d. CO ₂ Absorbent Canister and Gas Cooler	109
	e. Oxygen Uptake Tests	112
	f. SCBA Prototype Weight	118
	g. Wearability	121
APPENDIX		
A	DEVELOPMENT OF THE PRESSURE EQUATION FOR THE CO ₂ ABSORBENT CANISTER.	131
B	DETAILED ANALYSIS OF RESPIRATORY COOLING.	139
C	DELTA P COMPUTER MODELING	147
D	TEST PLAN FOR UNMANNED TESTS CONDUCTED AT REIMERS CONSULTANTS	167

LIST OF FIGURES

FIGURE	TITLE	PAGE
1	Left Side View	5
2	Front View	12
3	Right Side View.	13
4	Rear View (Looking Forward).	14
5	Harness-Right View	15
6	Harness-Front View	16
7	Functional Schematic	18
8	Gas Supply	21
9	Canister Housing, Exploded View.	25
10	CO ₂ Canister, Exploded View.	26
11	Frame Assembly Front View.	28
12	Frame Assembly Rear View	31
13	Demand Regulator Exploded View	32
14	Demand Regulator Installation.	33
15	Spring/Pulley Assembly	34
16	Supply/Exhaust Bellows Installation.	37
17	Master Bellows	38
18	SCBA Design Schematic.	40
19	Design Concept "A" for Gas Scrubbing/Cooling	53
20	Design Concept "B" for Gas Scrubbing/Cooling	55
21	Flow Path Key for Air Force AP Program (AFDP).	65
22	SCBA Drawing Tree.	72
23	Koegel Valve Performance, Sine-wave Respiratory Flows.	91

LIST OF FIGURES (CONCLUDED)

FIGURE	TITLE	PAGE
24	Mouthpiece ΔP Data for Relief Valve set at 1.4 Inches H_2O . . .	92
25	Mouthpiece ΔP Data for Relief Valve set at 1.8 Inches H_2O . . .	94
26	Mouthpiece Respiratory Pattern	95
27	First Stage Regulator Outlet Pressure.	100
28	Supply Gas Flow Rates.	105
29	Oxygen Uptake Data Reliability Assessment.	119
C-1	Design A, 200 lpm, Breath Volume, Liters versus Mouthpiece Pressure, cm H_2O	151
C-2	Design A, 300 lpm, Breath Volume, Liters versus Mouthpiece Pressure, cm H_2O	153
C-3	Design A, 350 lpm, Breath Volume, Liters versus Mouthpiece Pressure, cm H_2O	155
C-4	Design A, 400 lpm, Breath Volume, Liters versus Mouthpiece Pressure, cm H_2O	157
C-5	Design B, 200 lpm, Breath Volume, Liters versus Mouthpiece Pressure, cm H_2O	159
C-6	Design B, 300 lpm, Breath Volume, Liters versus Mouthpiece Pressure, cm H_2O	161
C-7	Design B, 350 lpm, Breath Volume, Liters versus Mouthpiece Pressure, cm H_2O	163
C-8	Design B, 400 lpm, Breath Volume, Liters versus Mouthpiece Pressure, cm H_2O	165
D-1	Breathing Resistance Test Setup.	181
D-2	Inspired Gas CO_2 Test Setup.	182

LIST OF TABLES

TABLE	TITLE	PAGE
1	Definitions of Symbols.	41
2	Absorbent Canister Parameters	56
3	SCBA Breathing Profile.	59
4	Critical Materials and Components	61
5	Miscellaneous Components.	62
6	Weight Summary.	62
7	Input Information for Design A, Scrubber and Cooler Side-by-Side.	66
8	Input Information for Design B, Scrubber above Cooler	68
9	Results of Computer Simulated Breathing Resistance Tests. . .	70
10	Prototype SCBA Baseline Configuration	73
11	Actual Versus Predicted Pressure Drops.	89
12	ΔP for Selected Components.	90
13	First Stage Regulator Outlet Pressure for BioMarine 60 #200840.	98
14	First Stage Regulator Outlet Pressure for Sherwood Selpac Regulator.	99
15	Supply Gas Flow Test, Positive Pressure Spring Engaged. . . .	102
16	Supply Gas Flow Test, Bellows Spring Not Connected.	103
17	Supply Gas Flow Test, No Spring/Relief Valve.	104
18	CO ₂ Absorbent Test Data	106
19	Gas Cooler Test With CO ₂	110
20	Gas Cooler Test Without CO ₂	111
21	Oxygen Uptake Test No. 3.	113
22	Oxygen Uptake Test No. 4.	114

LIST OF TABLES (CONCLUDED)

TABLE	TITLE	PAGE
23	Oxygen Uptake Test No. 1	115
24	Oxygen Uptake Test No. 2	116
25	Oxygen Uptake Test No. 5	117
C-1	Air Force Delta P Program Input Data Listing	149
C-2	Design A, 200 LPM.	150
C-3	Design A, 300 LPM.	152
C-4	Design A, 350 LPM.	154
C-5	Design A, 400 LPM.	156
C-6	Design B, 200 LPM.	158
C-7	Design B, 300 LPM.	160
C-8	Design B, 350 LPM.	162
C-9	Design B, 400 LPM.	164

SECTION I

INTRODUCTION

1. OBJECTIVE

a. General.

The objective was to design and develop a prototype, self-contained breathing apparatus (SCBA) suitable for U.S. Air Force fire fighting and to the operations of at least two hours duration in a chemical, biological, radiological (CBR) environment. Primary design considerations were reduction of the SCBA's profile and weight from that which is currently available, while providing capability of breathing air for two hours under actual fire fighting conditions.

b. Scope.

A two-phased development sequence was performed. Phase 1 consisted of the design and fabrication of a breadboard model which was tested with a breathing machine. After the Phase 1 effort was approved by the U.S. Air Force Program Manager, Phase 2 was conducted to design and fabricate a prototype model. The prototype was then subjected to full-scale breathing machine testing to determine its compliance with contractual requirements prior to delivery of the unit to the Air Force for manned testing. During Phase 2, monodetail engineering drawings meeting DOD-D-1000 Level-3 requirements were prepared where part design was expected to be final and to Level-2 for those

parts not considered to be of final design.

c. Technical Requirements.

(1) The SCBA shall be designed as a semi-closed, pressure demand system to be worn in a vest-type arrangement under a protective suit. The SCBA must provide two hours of breathing air under actual fire fighting conditions.

(2) The SCBA shall have a maximum weight of no more than 30 pounds when fully charged for operational use. However, an SCBA which weighs less than 30 pounds is highly desirable.

(3) Consistent with reasonable costs for a production model, the SCBA shall be fabricated in the smallest size and be of the lightest weight attainable with commercially available system components, such as tubing, valves, cylinders, etc.

(4) The SCBA shall be a simple, rugged, and easily maintained design which minimizes fatigue while permitting adequate mobility of the user.

(5) The SCBA shall be designed so that in the pressure demand mode, the inhalation pressure does not fall below 1 cm of H_2O , and exhalation pressure does not rise above 8 cm of H_2O at an instantaneous rate of 400 liters per minute (lpm) of breathing gas.

(6) The CO_2 absorbent canister shall be designed for easy changing of the absorbent in the field; a pre-packaged, drop-in, absorbent element is highly desirable.

(7) The design shall incorporate a cooling system which provides 400 Btu of cooling capacity for cooling of inspired breathing gas. The cooling system shall require no electrical power.

2. BACKGROUND

A review of the operational experiences of the Air Force fire fighting and rescue teams has shown that their effectiveness could be improved substantially if they had an improved self-contained breathing apparatus (SCBA) available. Existing commercial equipment is not directly adaptable to Air Force use because of a number of operational factors peculiar to the Air Force applications (e.g., survivability in a CBR environment). Breathing apparatus currently in use by the Air Force is bulky, difficult to don, and lacks endurance.

Recent tests conducted by the U.S. Air Force School of Aerospace Medicine (USAFSAM), and investigations by the U.S. Fire Administration and Federal Emergency Management Agency (USFA/FEMA), indicate that two primary factors, safety and serviceability, are questionable declarations for SCBA presently in use.

USAFSAM reports that the two types of SCBA that are most widely used in civilian and U.S. Air Force fire departments, Scott Air-Pak and Mine Safety Appliance (MSA Model 401), will not provide the minimum 30-minute service duration, and only support life from 10 to 20 minutes depending upon the fire fighter's size, weight, and physical exertion. Another significant test result indicated, contrary to manufacturers' claims, negative pressures do occur with great regularity inside the faceplate when in the pressure-demand mode. Noted, too, were extremely high inspiratory resistances when

cylinder pressure drops below 500 psi, which then triggers the low pressure alarm device. In some cases this could be dangerous to the user, because the onset of high breathing resistance might occur at the most inopportune time (i.e., when the fire fighter is attempting to egress from a life-threatening environment). It was also noted that, contrary to manufacturers' instructions for SCBA use, the air supply remaining in the cylinder when the alarm activates is considerably less than five minutes for a person performing work typical of a fire fighter.

3. GENERAL DESCRIPTION

a. Physical Characteristics Summary.

The prototype SCBA, developed to meet the technical requirements of paragraph 1.c., functions in a manner similar to a classic semi-closed circuit breathing apparatus. It consists principally of a gas (60 percent O_2 and 40 percent N_2) supply system, a bellows assembly, a CO_2 absorbent canister, and a breathing gas cooling assembly mounted on an aluminum frame. The SCBA is worn as a backpack with the supply and exhaust hoses over the user's shoulders to the mouthpiece. The SCBA donned by a user is illustrated in Figure 1.

The dimensions of the prototype SCBA are 26 inches in length, 17 inches in width, and 9 inches in depth. In a fully charged condition, it weighs 34 pounds and provides a two-hour supply of breathing gas for the user.

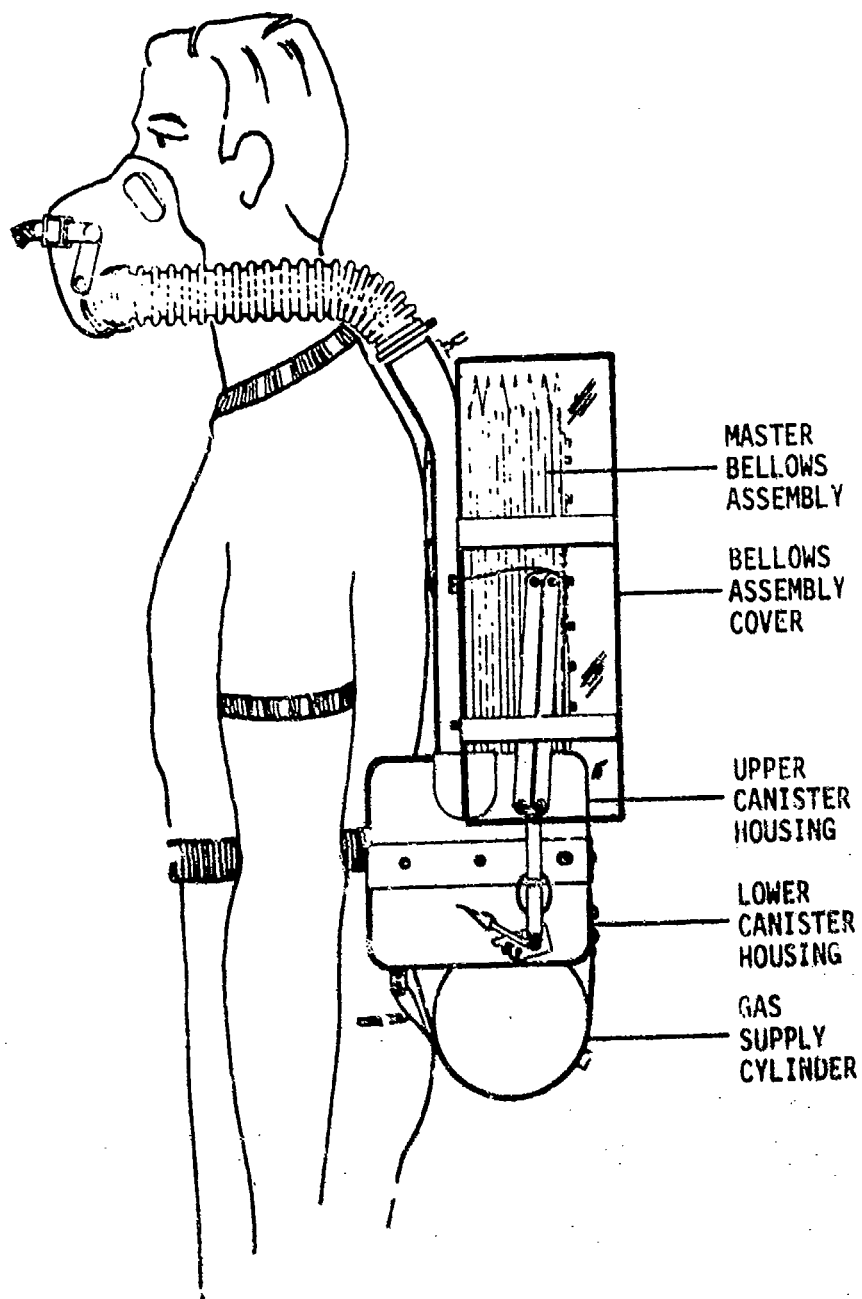


Figure 1. Left Side View.

b. Operation.

The SCBA user exhales through the mouthpiece and exhalation hose into the master bellows assembly through the CO₂ absorbent bed and the gas cooling assembly. As the master bellows expands, the supply and exhaust bellows also expand. The supply bellows fills with new breathing gas from the supply cylinder and the exhaust bellows fills with gas drawn from the user. As the user inhales through the mouthpiece and supply hose, the master bellows contracts, causing the supply and exhaust bellows to contract as well. The supply bellows discharges its oxygen-rich contents into the master bellows, while the exhaust bellows discharges its contents to the outside atmosphere and to the CO₂ absorbent bed. The inhalation/exhalation cycle continues in this manner for the two-hour duration. When the breathing gas pressure in the supply cylinder decreases to 500 psi, a low pressure alarm sounds to warn the user.

4. UNMANNED TEST AND EVALUATION SUMMARY

Unmanned tests were conducted at Reimers Consultants, Falls Church, Virginia, to determine the prototype SCBA's compliance with contractual and common sense requirements prior to delivery of the prototype to the Air Force for manned testing. These tests were conducted in accordance with Test Plan For Unmanned Tests To Be Conducted At Reimers Consultants, dated July 1981. The test plan is included in this report as Appendix D.

To evaluate SCBA performance in the areas of

- o duration of gas supply

- o duration of CO₂ scrubber
- o inspired pO₂ performance as a function of B and respirator minute volume (RMV).
- o breathing resistance and maintenance of positive facepiece pressures
- o cooler performance and duration
- o weight

tests were conducted to determine:

- o breathing resistance
- o first stage regulator performance
- o supply gas flow rates
- o CO₂ scrubber and gas cooler performance
- o oxygen uptake
- o wearability

5. CONCLUSIONS/RECOMMENDATIONS

a. Conclusions.

The unmanned testing demonstrated that the prototype SCBA meets all of the performance requirements except for weight. Specific conclusions regarding critical areas that were evaluated are:

(1) Duration of Gas Supply. At the design condition of a 40-lpm RMV, the supply will last the required two hours with about a ten-minute margin. The gas supply rate is not linear with RMV below 40 lpm. Thus, exercise profiles

with alternately higher and lower RMVs, but still a 40-lpm average RMV, will result in slightly shorter gas supply duration.

(2) Duration of CO₂ Absorbent Canister. The CO₂ absorbent canister met the required endurance of two hours during the test program.

(3) Inspired pO₂ Performance. The inspired pO₂ performance appeared completely acceptable under all test conditions. During manned tests, the inspired pO₂ should stay within the range of 30 to 50 percent.

(4) Breathing Resistance. The breathing resistance values were higher than predicted, due mostly to higher than expected resistance values in the facepiece one-way valves. The prototype will maintain a positive facepiece pressure at peak flow rates up to 250 lpm (80-lpm RMV), with a static bellows pressure of approximately 1.3 inches water. With an increase in static bellows pressure of 0.5 inch water, facepiece pressure would remain positive to peak flow rates of 350 lpm (111.6-lpm RMV).

(5) Cooler Performance and Duration. The cooler seemed to work as well or better than expected, even though the container material had to be changed to 16-gauge aluminum for fabrication reasons. The cooler continued to cool for at least two hours in all tests. The rate of energy removed by the cooler also appeared reasonably stable, although the difficulty in getting good estimates of entering enthalpy made all of the heat transfer rate measurements highly approximate.

(6) Weight. The prototype SCBA weight, fully charged, is 34 pounds. With production tooling, use of a reinforced fiberglass gas bottle, L10H versus

Sodasorb[®], dry ice versus water ice, and structural refinements, the weight can be readily reduced to about 28 pounds.

b. Recommendations.

(1) Proceed with manned testing.

(2) Commence advanced development for design and production of ten pre-production prototypes for service test and evaluation.

SECTION II

TECHNICAL DESCRIPTION

1. DESIGN DESCRIPTION

a. General System Description.

(1) Physical. The prototype Self-Contained Breathing Apparatus (SCBA) for fire fighting and rescue is designed as a semi-closed, pressure demand system to be worn as a backpack. It uses commercially available system components, has a low profile, is relatively light, and provides two hours of breathing air.

The SCBA consists principally of a gas supply system, the canister housing which contains a CO₂ absorbent canister and a gas cooler canister, a bellows assembly, associated plumbing and hoses, and a facepiece. The top assembly design and general arrangement of the subsystems are illustrated in Figures 2 through 6.

The front view depicts the side of the SCBA that is worn against the user's back (Figure 2), except for the facepiece and hoses. The facepiece is worn to cover the user's mouth and nose, and the inhalation and exhalation hoses lead over the user's right and left shoulders, respectively. The supply and exhaust bellows pressure taps shown in Figure 2 were installed for acquisition of test data during test and evaluation of the prototype. They will not be required in the production unit design. The shoulder straps and belt have been omitted from Figure 2 for clarity. However, they are illustrated in

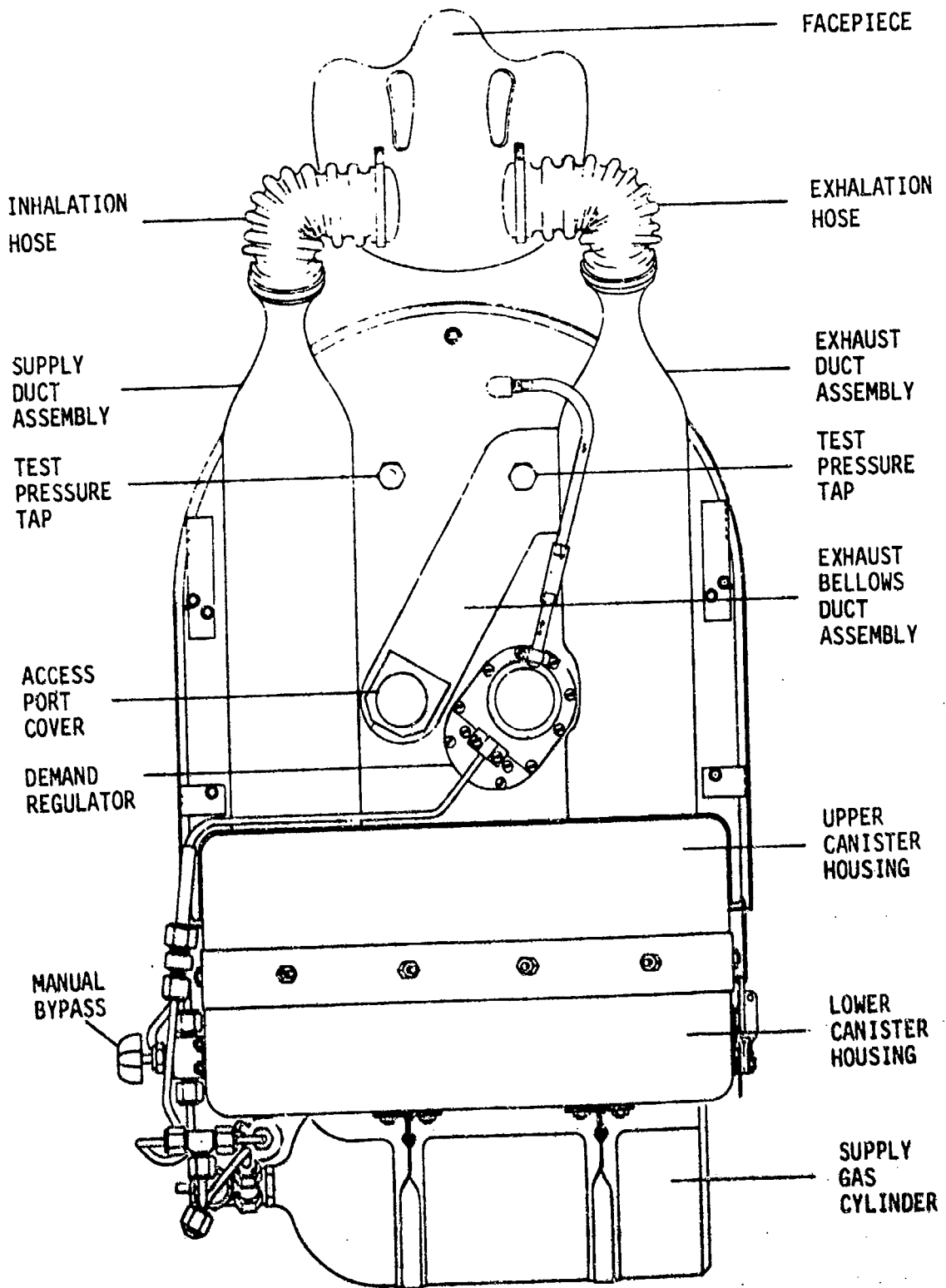


Figure 2. Front View.

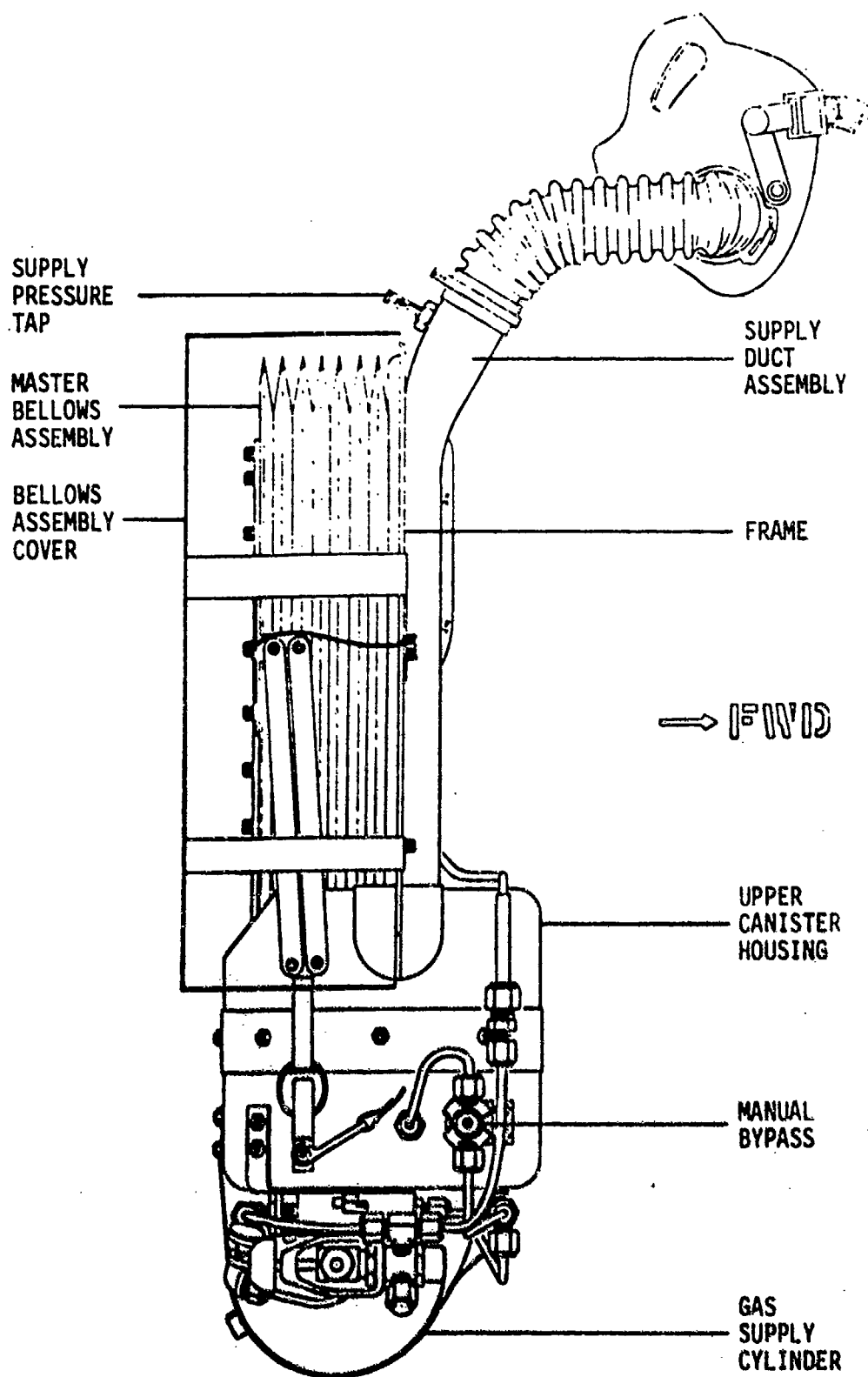


Figure 3. Right Side View.

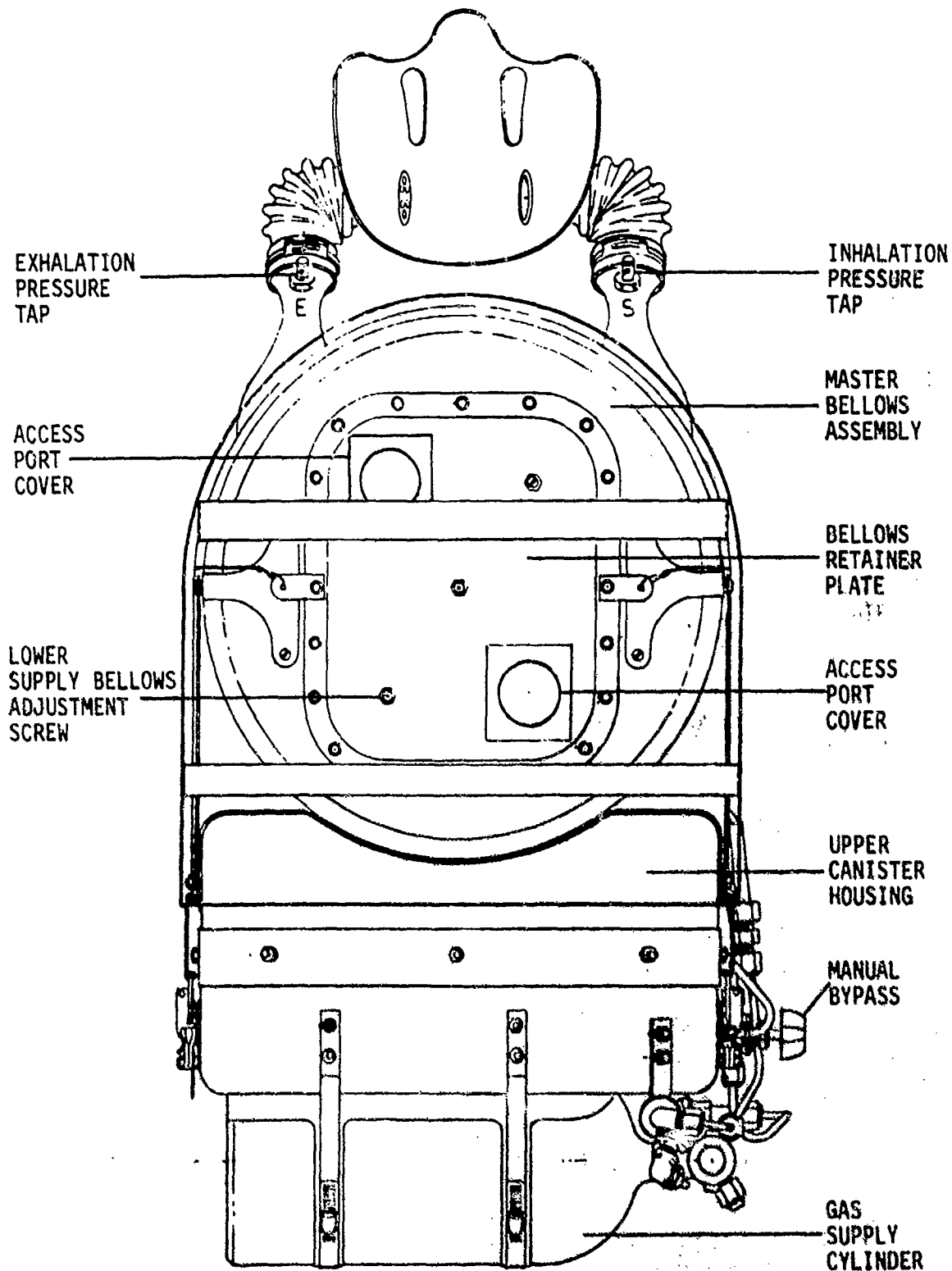


Figure 4. Rear View (Looking Forward).

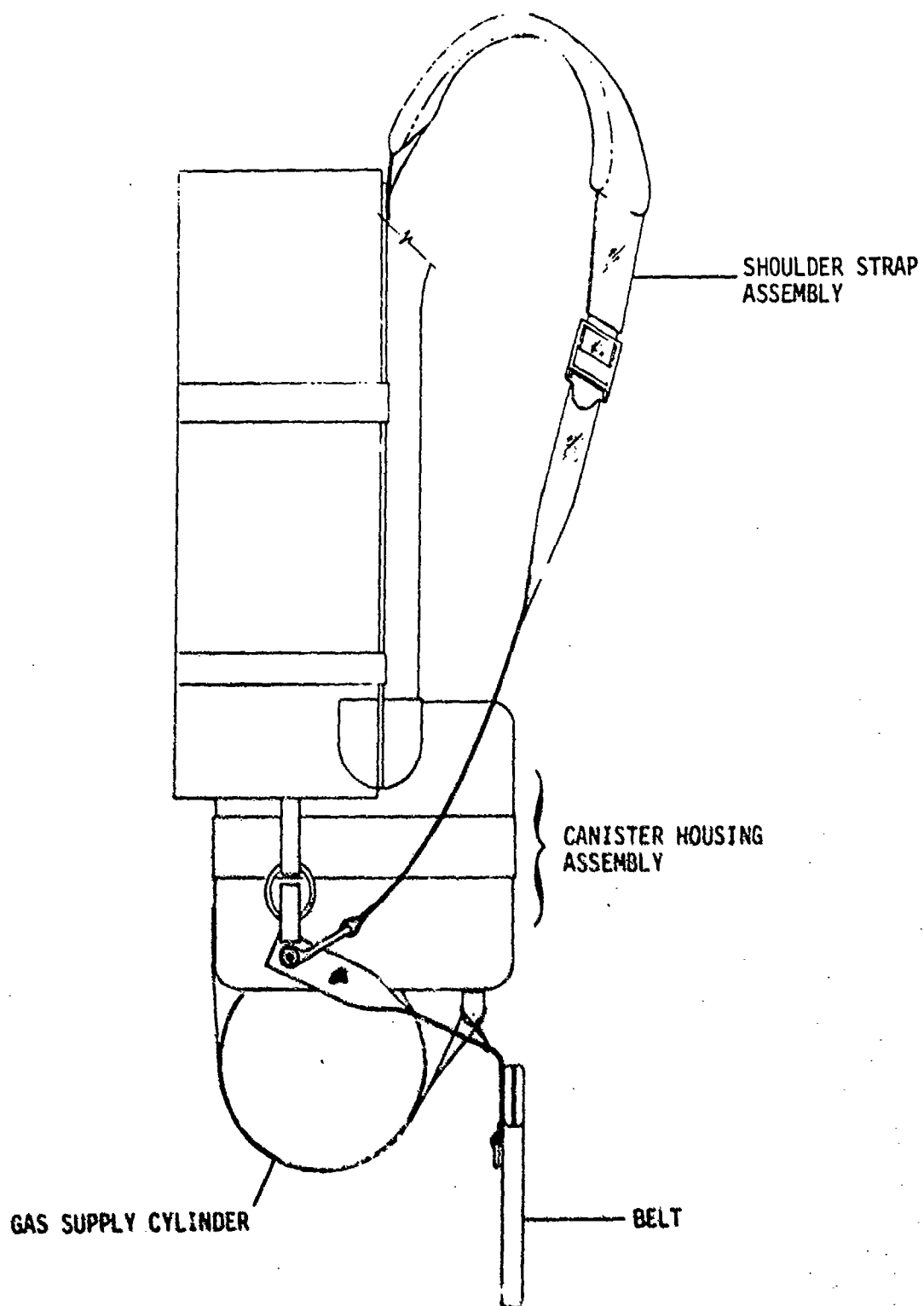


Figure 5. Harness-Right View.

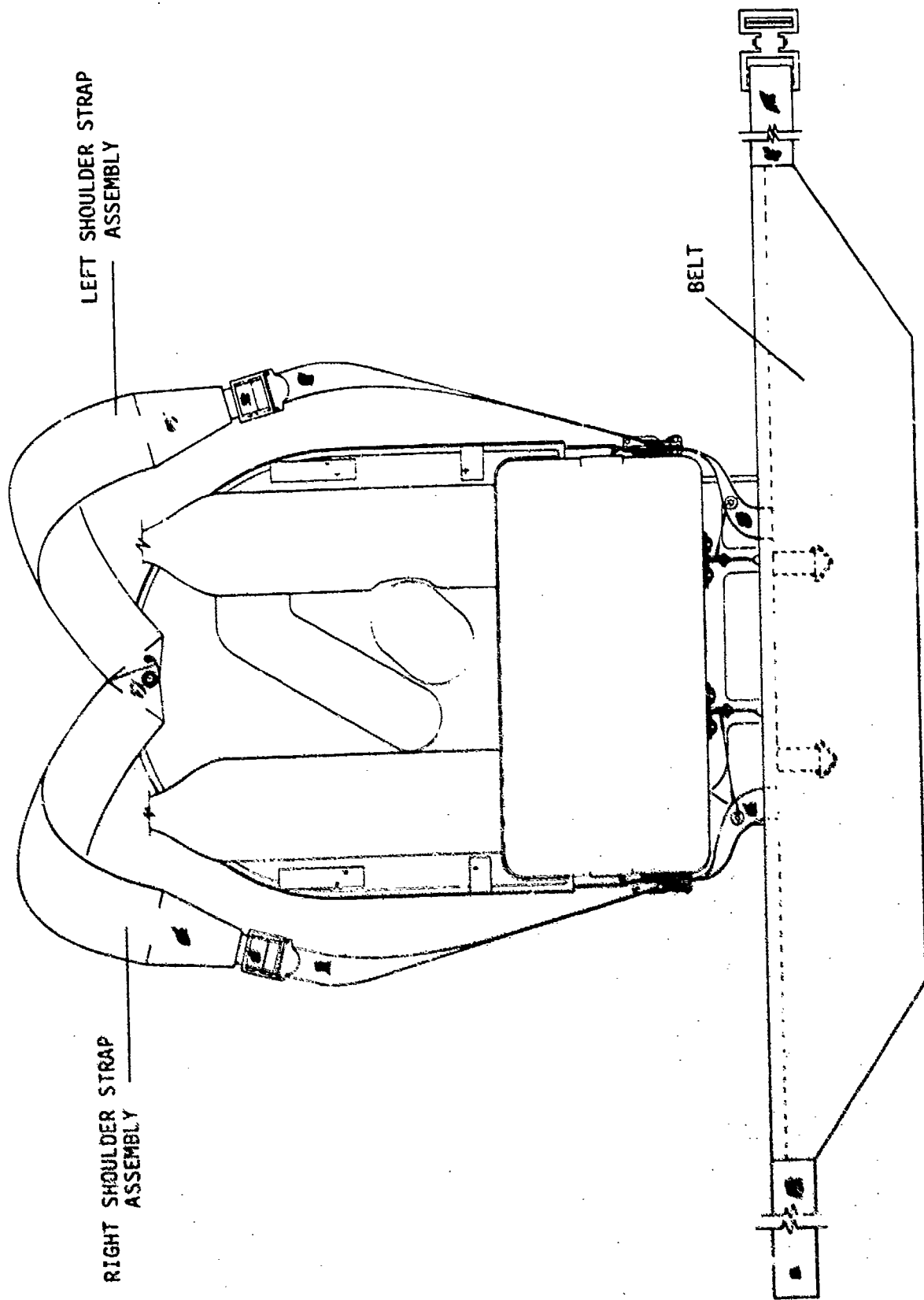


Figure 6. Harness-Front View.

Figures 5 and 6.

The right side view (Figure 3) illustrates the SCBA profile as seen from looking toward the user's right side. Again, the shoulder straps and belt have been omitted for clarity. The inhalation and exhalation pressure taps, shown installed at the top of the supply and exhaust duct assemblies respectively, were installed for acquisition of prototype test data and will not be required on the production unit. The master bellows assembly cover has been constructed from transparent plexiglass material to facilitate prototype test and evaluation. The cover final design would utilize an opaque plastic material and a contoured configuration.

The rear view (Figure 4) depicts that side of the SCBA seen when looking at the user's back from a position behind him. In this view, the prototype design permits the retainer plate end of the master bellows assembly to be seen through the transparent cover for the master bellows assembly. The access port covers shown on the retainer plate are for access to the supply and exhaust bellows assemblies. This is a prototype test and evaluation requirement only and is not a final design requirement.

Figures 5 and 6 illustrate the design of the shoulder straps and belt for securing the SCBA to the user.

(2) Functional. The SCBA functional schematic is illustrated in Figure 7. Gas flow into the apparatus is controlled principally by a fixed flow rate orifice and the supply bellows. The fixed flow rate orifice provides a steady flow of approximately 1.0 liters per minute (lpm). The supply

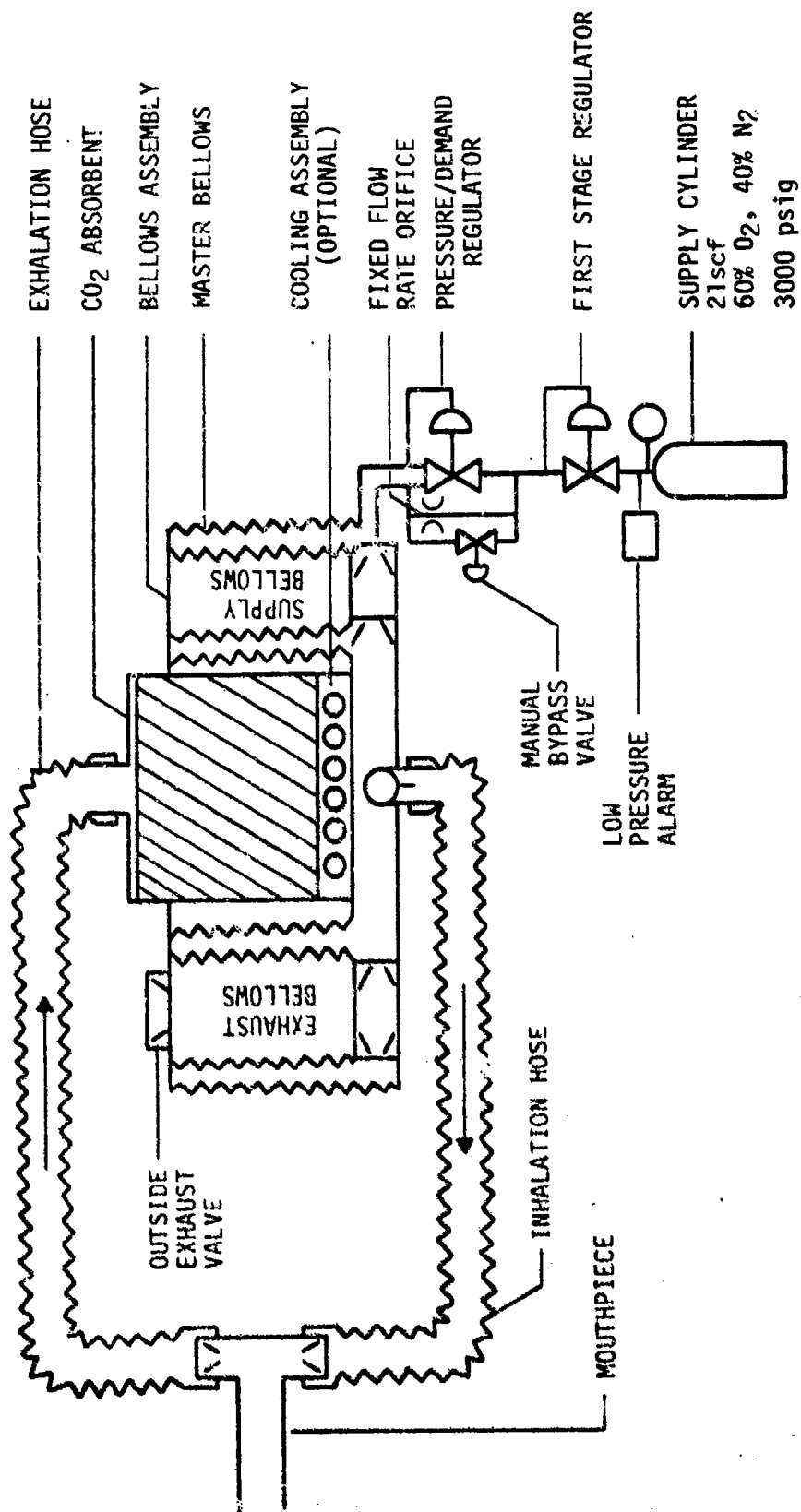


Figure 7. Functional Schematic.

bellows provides an additional flow that is proportional to the user's respiratory minute volume (RMV). The combination of a small fixed flow rate with a variable supply rate proportioned to the user's RMV provides for acceptable minimum inspired partial pressure of oxygen (pO_2) levels in a failure mode condition, while yet providing nearly maximum gas economy. In case of failure of the demand regulator or supply bellows, gas may be added to the system via the manual bypass valve. Further, should the master bellows "bottom," resulting in a negative pressure inside the bellows, the demand regulator would add gas directly through the supply bellows to relieve the negative pressure.

Gas flow out of the apparatus, at a metered rate proportioned to the user's RMV, is ensured by the exhaust bellows. Any additional exhaust flow that may be necessary simply flows out directly through the exhaust bellows. At first glance, the exhaust bellows may appear unnecessary; however, it provides two useful functions. First, it provides a degree of redundancy with the supply bellows. For the net supply gas flow through the unit to fall below design levels, both a supply bellows and an exhaust bellows must fail. Further, the metered exhaust flow capability afforded by the exhaust bellows makes it possible to use the apparatus in a positive pressure mode.

The master bellows functions as both a breathing bag and as the "master" that drives the "slave" exhaust and supply bellows. The supply and exhaust bellows are located inside the master bellows and are installed so that their expansion and contraction follow that of the master bellows. The supply and exhaust bellows are evenly spaced around the periphery of the master bellows. Consequently, the net ratio of supply or exhaust bellows displacement to master bellows displacement remains relatively constant, even if the master

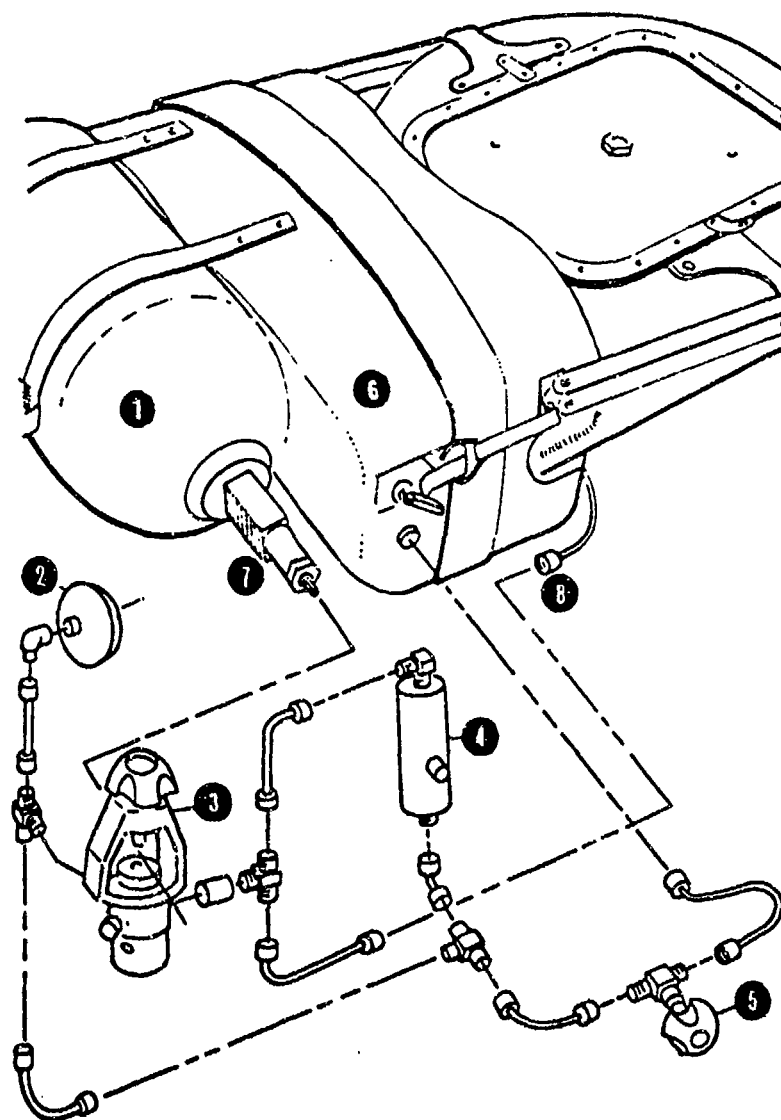
bellows should displace unevenly.

CO₂ level control is achieved by passing the user's exhaled gas through a CO₂ absorbent bed. Medical grade, high-performance Sodasorb® is the CO₂ absorbent chemical. Following the CO₂ absorbent bed, a gas cooling assembly is used. Its use, however, is optional. Without gas cooling, the gas supplied to the user will quickly become warm and saturated. Gas cooling is not a physiological necessity; however, it may very well prove to be an operational necessity, especially during long exposures. Gas cooling, if desired, is provided by the use of a solid-liquid phase change in confined water.

b. Subsystem Design.

(1) Gas Supply. The gas supply subsystem consists of a high pressure gas storage cylinder and associated plumbing, valves, and regulators to provide a steady flow of breathing gas to the supply bellows. Figure 8 is an expanded view of the gas supply components and plumbing with identification of the major items. All of the components, except the demand regulator valve, in the gas supply subsystem are commercially available with proven performance.

(a) Gas Supply Cylinder (Figure 8, item 1). The cylinder used in the prototype design is manufactured by Luxer and marketed under part number L21W. It is a filament wound aluminum cylinder manufactured and tested in compliance with U.S. Department of Transportation Exemption 7235 and the Canadian Transport Commission Special Permit 1116. The cylinder was selected for use in the prototype based on the capacity requirements analysis of section 2.g.,



1. GAS CYLINDER
2. CYLINDER PRESSURE GAUGE
3. FIRST STAGE REGULATOR
4. CYLINDER LOW-PRESSURE ALARM
5. MANUAL BY-PASS
6. HOUSING BOTTOM
7. CYLINDER VALVE
8. DEMAND REGULATOR SUPPLY LINE

Figure 8. Gas Supply.

its proven performance, and availability. This cylinder should deliver 20.3 standard cubic feet (scf) of 100 psig, which is well in excess of the anticipated requirement of 16.1 scf. The cylinder characteristics are:

Length, in. (mm)	11.3 (287)
Diameter, outside (OD), in. (mm)	5.4 (137)
Pressure, working, psi (bar)	3000 (207)
Capacity	
Air, scf (liters)	21.0 (595)
Water, lb. (kg)	6.0 (2.7)
in. ³ (liters)	166 (2.7)
Weight, lb. (kg)	5.5 (2.5)
Threads, UNF	0.750-16

The weight of 5.5 pounds is a little over 16 percent of the total weight of the fully charged prototype SCBA. Use of a fiber-reinforced gas cylinder in the production design can reduce the weight by as much as 1.9 pounds.

(b) Cylinder Valve (Figure 8, item 7). The cylinder valve is of the packed type, nonrising stem, flanged design manufactured by Sherwood Selpac Corporation, primarily for use on medical gas cylinders for oxygen service. The manufacturer's part number is KVA8754G-32. The valve body is fabricated from a brass forging. The stem and plug are naval brass, and the packing is teflon. Incorporated in the valve is a safety device, type CG-4, frangible burst disc, backed with 165°F (nominal) fusible metal.

(c) Cylinder Pressure Gauge (Figure 8, item 2). The cylinder pressure gauge is manufactured by Sherwood Selpac Corporation under part number 4300-2.

(d) First Stage Regulator (Figure 8, item 3). The first stage regulator is manufactured by BioMarine Industries of Malvern, Pennsylvania under part number 200840.

(e) Cylinder Low Pressure Alarm (Figure 8, item 4). The low pressure alarm is manufactured by BioMarine Industries of Malvern, Pennsylvania under part number 200847.

(f) Manual Bypass Valve (Figure 8, item 5) The bypass valve is a forged body regulating stem and shutoff valve, part number BORS2, manufactured by the Whitey Company of Oakland, California. The body is brass, the stem and bottom gland are type 316 stainless steel, the packing is pure high density TFE cylinder machined from extruded solid rod, and the handle is a black molded phenolic knob with cadmium plated hardened steel set screws. The technical data for the valve are:

Orifice size, in.	0.080
Flow coefficient, C_v	0.09
Pressure rating @ 70°F, psi	3000
Temperature rating, max. °F	450

(2) Canister Housing. The canister housing provides structural support for assembly of the unit and contains the CO₂ absorbent canister and the gas cooler canister. Its configuration is essentially rectangular and boxlike with the long dimension sides radiused to match the typical user's body curvature. The housing consists of top and bottom sections, each fabricated from fiberglass, which can be disassembled for installation/removal of the CO₂ canister and ice canister. Figure 9 illustrates an exploded view of the canister housing.

(a) CO₂ Canister. The CO₂ canister, item 2 as illustrated in Figure 9, is essentially rectangular with the long sides radiused to match the housing configuration. It is approximately 1.3 inches thick and contains 3.1 pounds of medical grade Sodasorb®. It is fabricated in two sections, a top and a bottom. The sides of the canister top and bottom sections are fabricated from stainless steel with the top of the top section and bottom of the bottom section fabricated from fine mesh stainless steel wire screen. Figure 10 is an exploded view of the CO₂ canister. Before filling the bottom section with Sodasorb®, a fiberglass pad is placed inside, which covers the screen bottom. After filling and preparing the Sodasorb® bed, the top section, with a fiberglass filter pad covering the inside of its wire screen top, is placed on top of the bottom section and sealed to it to complete the CO₂ canister assembly.

(b) Gas Cooler. The gas cooler canister, illustrated in Figure 9, has the same shape and essentially the same dimensions as the CO₂ absorbent canister. It is fabricated from sheet aluminum. External ribbing is used to facilitate gas flow and heat exchange. The canister is filled with

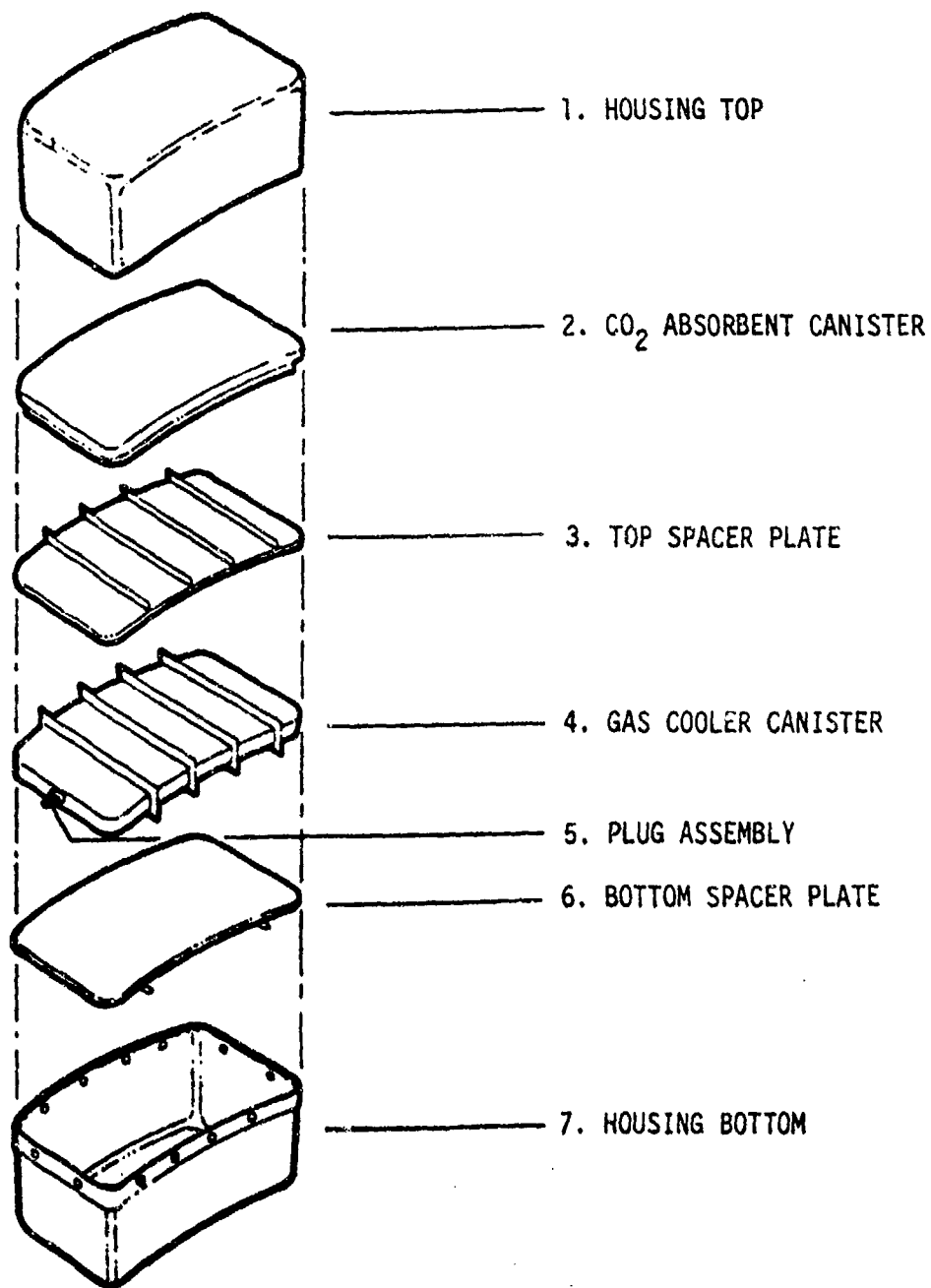


Figure 9. Canister Housing, Exploded View.

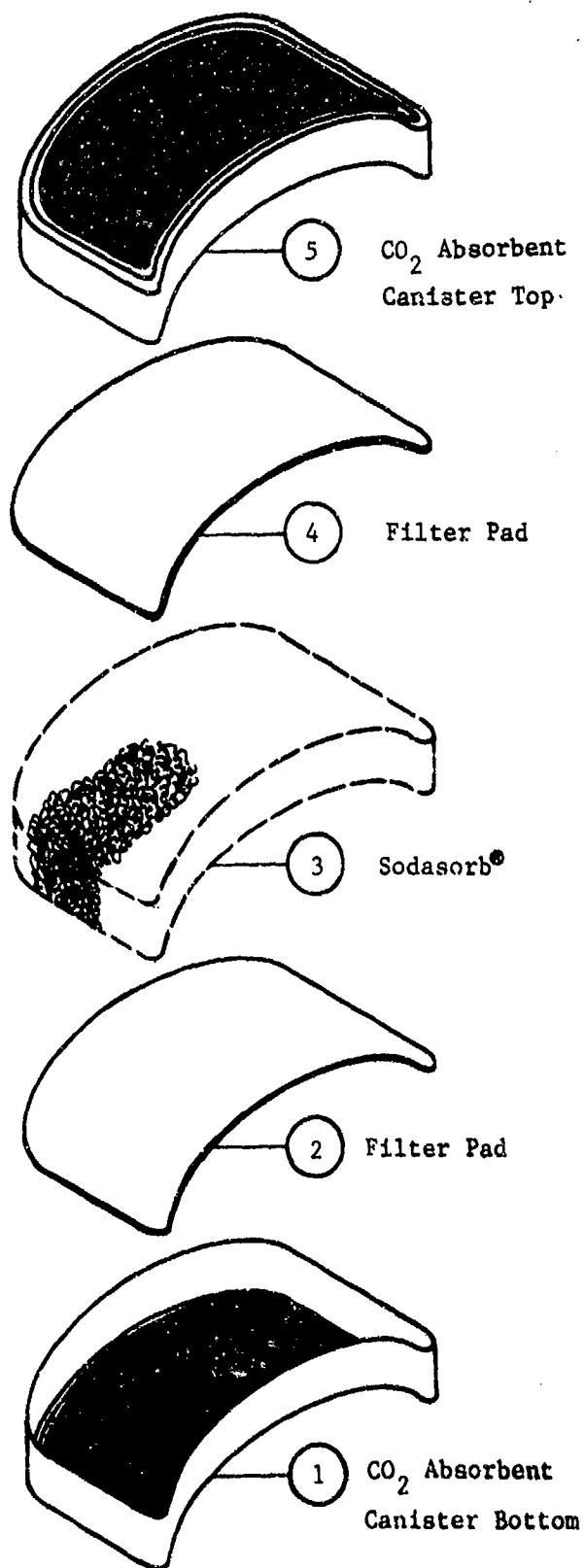


Figure 10. CO₂ Canister, Exploded View.

1100 milliliters of water, which is 90 percent of capacity. As a precaution against canister fracture, 10 percent of the volume is required for expansion which occurs when water freezes into ice. The canister fill hole and its special plug assembly are located on an end of the canister, as illustrated in Figure 9, item 4.

(3) Bellows Assembly.

A side view of the bellows assembly, as installed in the SCBA, is illustrated in Figure 3. The bellows assembly consists of the master bellows, two supply and two exhaust bellows, a spring assembly, a pulley assembly, demand regulator assembly and the frame assembly.

(a) Frame Assembly. The frame assembly serves as the main structural member for the top assembly of the SCBA, but is specifically designed as a chassis for the installation and system integration of the bellows assembly. The frame assembly consists of the frame, supply duct assembly, exhaust bellows duct assembly, supply bellows duct assembly, vane, and bellows mounting ring. All of these components are fabricated from sheet aluminum and welded into the frame assembly.

A front view photograph of the frame assembly (Figure 11) shows the supply duct (item 4), exhaust duct (item 5), and exhaust bellows duct (item 3) assemblies welded to the frame. In this photograph, the frame assembly and top (item 1) of the canister housing have been assembled. Also shown is the cavity (item 2) in the frame for installation of the demand regulator valve.



1. Center Housing Top
2. Supply Regulator Cavity
3. Exhaust Bellows Duct Assembly
4. Supply Duct Assembly
5. Exhaust Duct Assembly

Figure 11. Frame Assembly Front View.

The rear view of the frame assembly appears in Figure 12. The remaining components: (master bellows mounting ring [item 2], supply bellows duct assembly [item 1], and the vane [item 5]), are shown in this figure. The spring assembly and pulley assembly, assembled to the frame, also appear in Figure 12, but are not considered components of the frame assembly. Portions of the supply duct (item 4) and exhaust duct (item 3) are visible in the photograph of the rear view of the frame assembly.

(b) Demand Regulator Assembly. Breathing gas flow to the user is controlled by the demand regulator assembly. The demand regulator consists of a fixed flow rate orifice to provide a steady flow of approximately 1.0 liters per minute (lpm) and a tilt valve poppet assembly which provides additional flow that is proportional to the user's respiratory minute volume (RMV). The tilt valve poppet assembly is actuated by the expansion and contraction of the lower supply bellow assembly.

An exploded view of the demand regulator is shown in Figure 13. It is installed in the cavity (item 2) on the front side of the frame (Figure 11). A cutaway of the demand regulator installation in the frame cavity and under the lower supply bellows is shown in Figure 14.

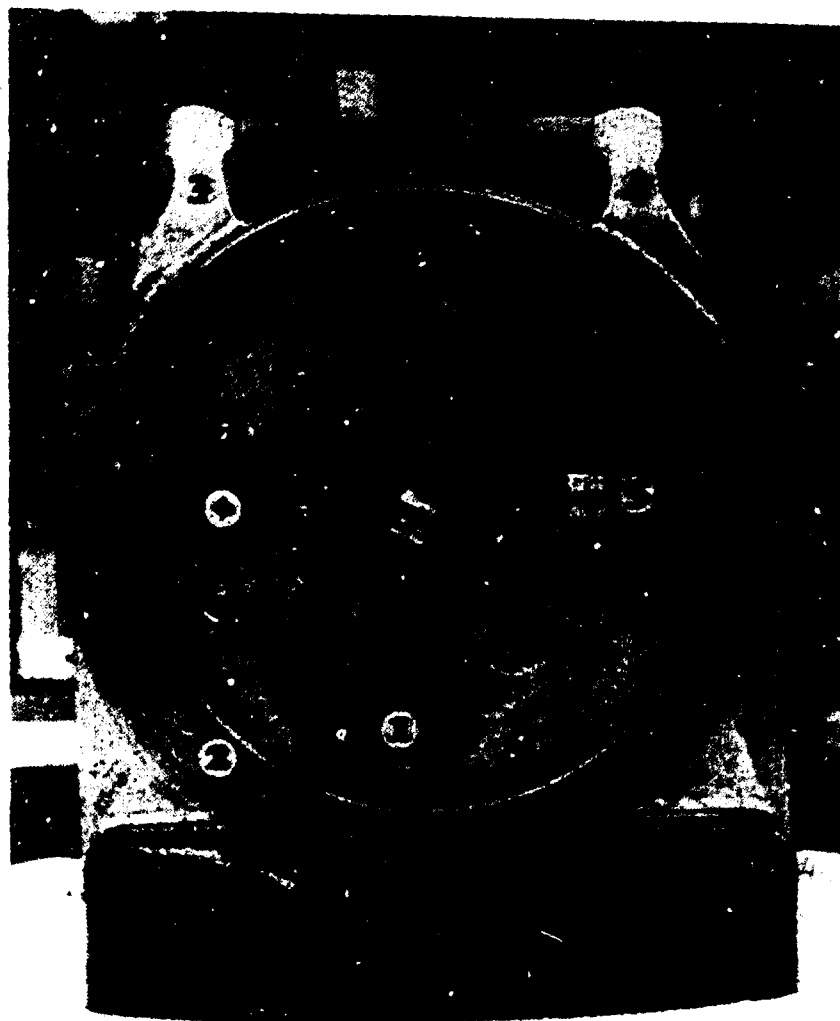
Breathing gas supply from the first stage regulator enters the demand regulator through the tube connector (Figure 13 and 14, item 1) and into the valve block's (Figure 13 and 14, item 2) cylindrical chamber containing the spring. From there the supply gas goes through the fixed orifice or jet (Figure 13, item 3) into the supply duct assembly (Figure 14, item 4) to provide a steady flow of approximately 1.0 lpm. If the user's RMV demands a higher flow

of supply gas, the expansion of the lower supply bellows (Figure 14, item 5) during exhalation will drop the pressure inside the supply duct assembly sufficiently to cause the demand regulator diaphragm (Figure 13 and 14, item 6) to move inward and contact the tilt valve hood (Figure 13 and 14, item 7) thus tilting the tilt valve seat (Figure 13 and 14, item 8) seal in the valve block and permitting additional supply gas to enter the supply duct assembly. The amount of additional supply gas will be proportional to the expansion of the lower supply bellows which in turn is proportional to the user's RMV.

(c) Spring/Pulley Assemblies. For operation in a positive pressure mode, a device must be installed which is continuously applying a force to cause the master bellows to collapse. The spring (item 1) and pulley (item 2) assemblies are installed to provide this function (Figure 15). The spring assembly, manufactured by John Evans, is commercially available and reliable performance has been demonstrated. The pulley assembly is a special design for the SCBA installation.

During the normal pressure mode operation, the spring assembly is disengaged. It is disengaged as it appears in Figure 15. The cable is faired under the pulley and through the pulley bracket slot. The cable is secured by the beaded end being on the side of the bracket away from the pulley.

In the positive pressure mode of operation, the spring assembly is connected to the inside of the master bellows retainer plate. This connection is made by removing the beaded end of the spring assembly cable from the slotted bracket next to the pulley assembly and threading the cable through the slot in the bracket at the inside center of the master bellows retainer plate. The beaded end secures the cable to the bracket during operation. In



1. Supply Bellows Duct Assembly
2. Master Bellows Mounting Ring
3. Exhaust
4. Supply
5. Vane

Figure 12. Frame Assembly Rear View.

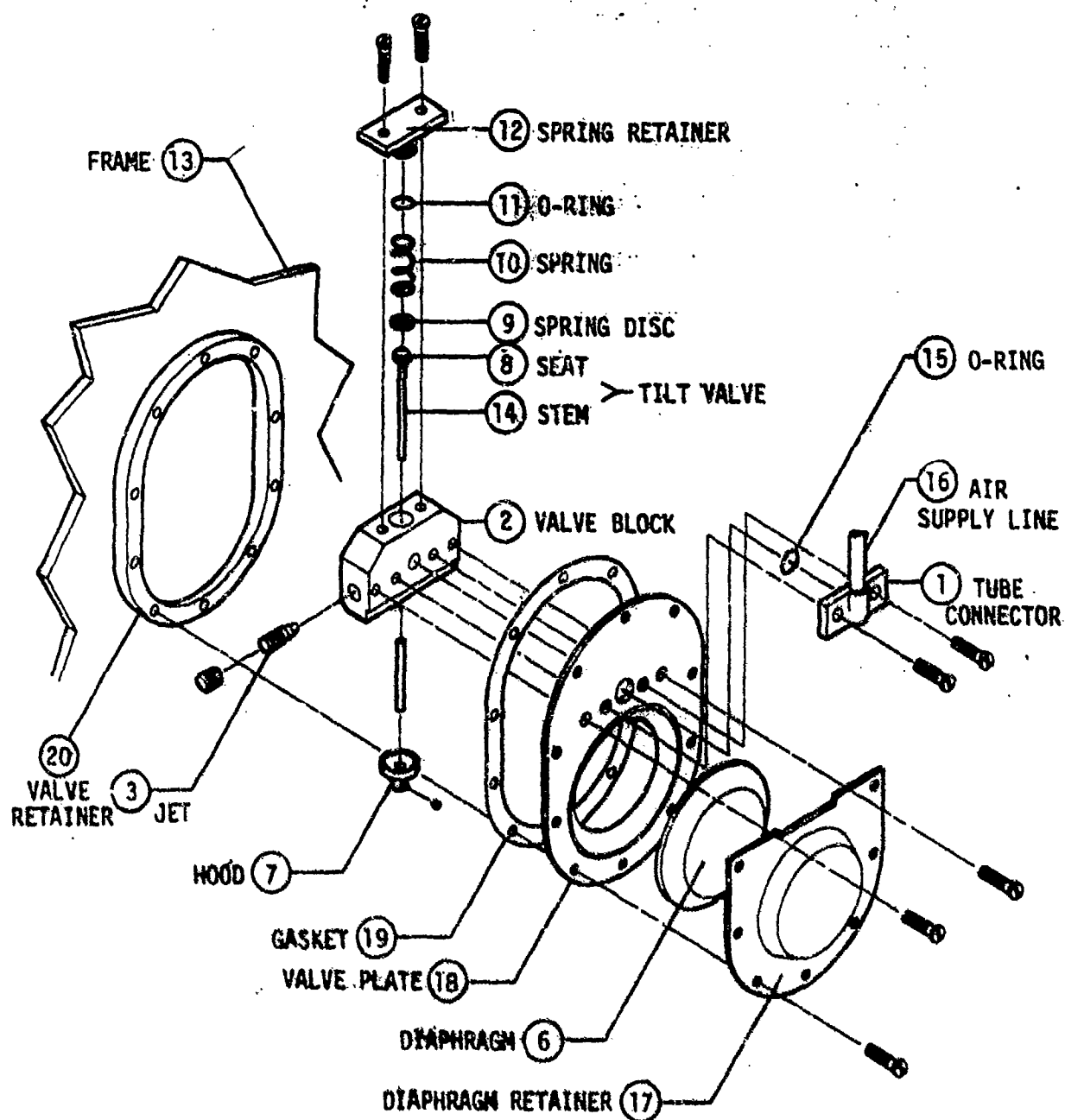


Figure 13. Demand Regulator Exploded View.

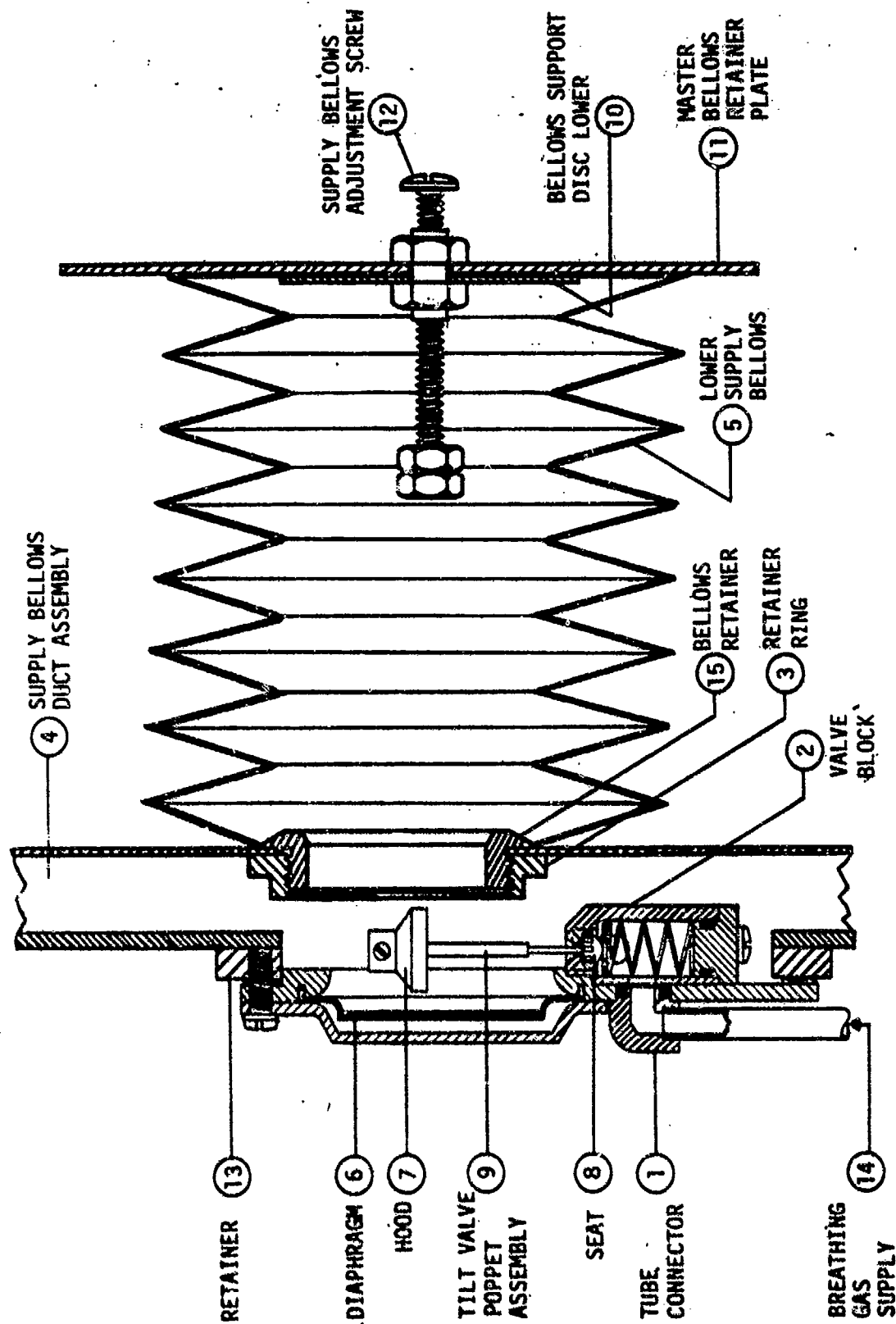
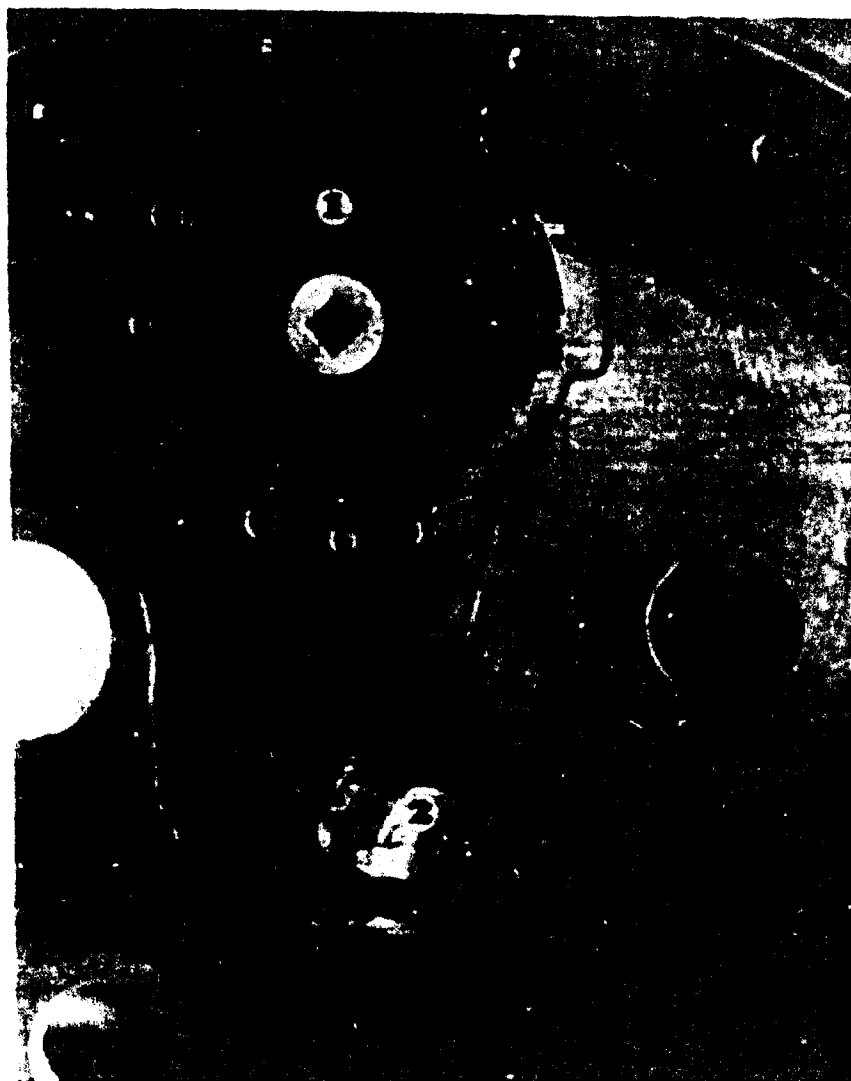


Figure 14. Demand Regulator Installation.



1. Spring Assembly
2. Pulley Assembly

Figure 15. Spring/Pulley Assembly.

this condition, the spring tension exerts a force attempting to collapse the master bellows and the force increases as the master bellows expands.

(d) Supply/Exhaust Bellows. The supply and exhaust bellows are manufactured by Gagne Associates of Bingham, New York. Each has eight convolutions and is fabricated from 0.010-inch thick estane material. The exhaust bellows has a 3.25-inch OD, a constant 1.12-inch ID, is open and flanged at both ends.

The supply bellows has a 3.5-inch OD, a 1.75-inch ID closed top end, and a 1.5-inch ID flange on the bottom open end. A cutaway of the installation of the lower supply bellows is illustrated in Figure 14. The closed top end is secured to the master bellows retainer plate (item 11) by the Bellows Support Disc Lower (item 10) and the Supply Bellows Adjustment Screw (item 12). The adjustment screw can be used to control the bottoming of the bellows by adjusting its length so that the bottom nut contacts the hood (item 7) on the Tilt Valve Poppet Assembly (item 9) and causes its seat (item 8) seal to be broken. When the seal is broken breathing gas is admitted into the supply duct assembly which increase the pressure in the bellows to stop the contraction of the bellows. The breathing gas flow rate through the tilt valve poppet assembly varies with the valve seat opening. The opening size can be adjusted by varying the length of the hood from the valve seat, which then changes the tilt angle of the seat. Shortening the length increases the opening.

Two supply and two exhaust bellows are utilized in the SCBA prototype design. They are installed on the rear side of the frame assembly in

an annulus-like cavity created by the master bellows mounting ring assembly to the frame and the supply bellows duct assembly attachment to the frame. The installation appears in Figure 16. The supply (item 2) and exhaust (item 3) bellows are alternately, and essentially, evenly spaced around the interior periphery of the master bellows when it is assembled to the mounting ring (item 1). It should be noted that the bellows depicted in Figure 16 are in various stages of installation and assembly. Using this system of "nested bellows," the SCBA provides a rate of gas supply that is always proportionate to the user's RMV, thus conserving the gas supply (thereby increasing the endurance). Also shown in Figure 16 are the spring assembly (item 4), pulley assembly (item 5), and the vane (item 6).

(e) Master Bellows. The master bellows functions as both a breathing bag and as the master that drives the "slave" exhaust and supply bellows. The master bellows is manufactured by Gagne Associates of Binghamton, New York. The principal dimensions are 13.5-inch OD, 10.5-inch ID, with 8 convolutions to the closed end. The 13.5-inch OD open end is flanged for attachment to the bellows mounting ring on the frame. An exploded view of the master bellows appears in Figure 17. The bellows convolutions are fabricated from 0.010-inch-thick estane material.

The top ends of all four of the supply and exhaust bellows, as illustrated in Figure 16, are attached to the inside of the master bellows retainer plate, illustrated in Figure 17. With the supply and exhaust bellows installed inside the convoluted bag of the master and their top ends physically attached to the master's retainer plate, their expansion and contraction follows that of the master.



1. Bellows Mounting Ring
2. Supply Bellows
3. Exhaust Bellows
4. Spring Assembly
5. Pulley Assembly
6. Vane

Figure 16. Supply/Exhaust Bellows Installation.

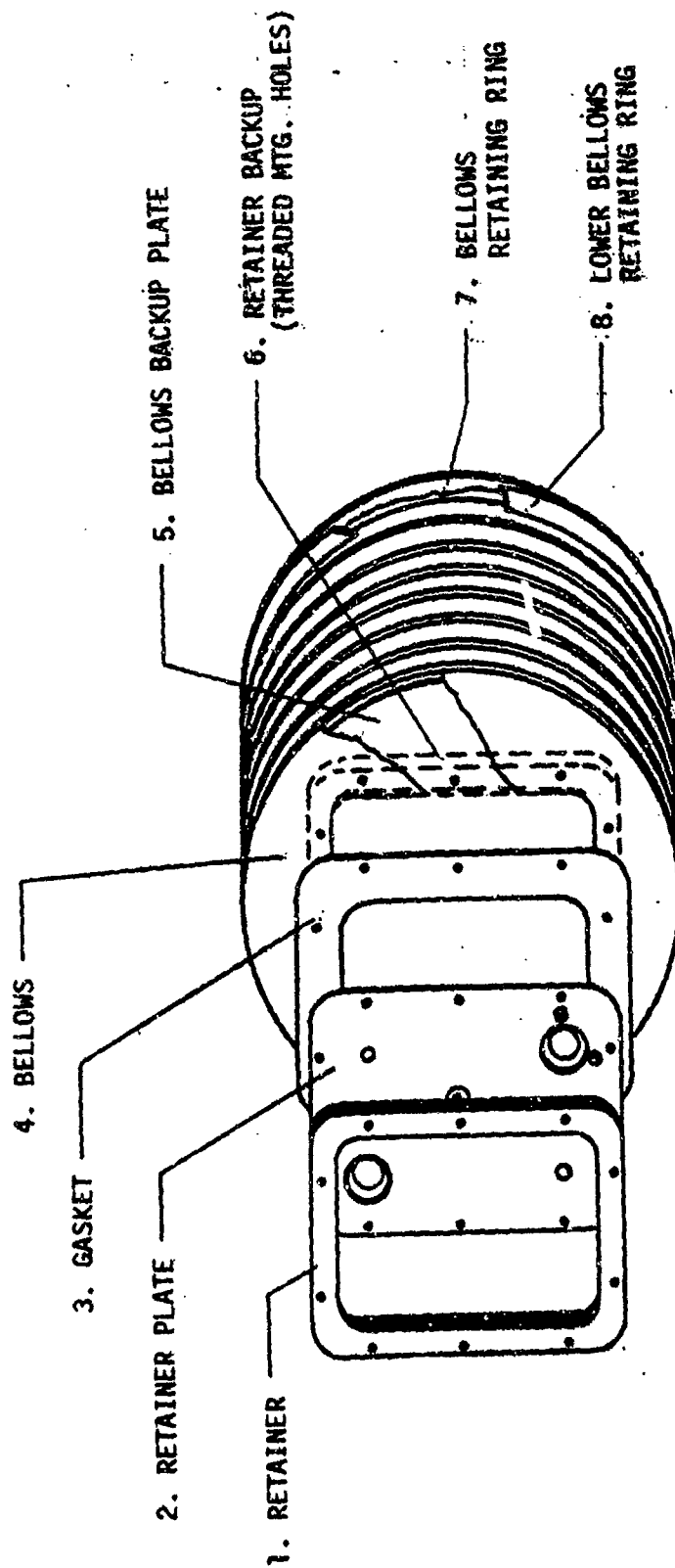


Figure 17. Master Bellows.

2. DESIGN ANALYSIS

a. Fundamental Relationships.

There are two basic steady state operating modes: pull-through and push-through. These operating modes are defined below. The design schematic is shown in Figure 18. Definitions of the symbols are given in Table 1.

(1) Pull-through. Volume losses (\dot{V}_{O_2} less \dot{V}_{CO_2} , \dot{V}_{sc} , \dot{V}_{EB}) exceed metered supply flow ($CV_B + 0.5F$) causing main bellows to bottom during inhalation and operate the demand regulator.

(2) Push-through. When operating in the push-through mode, the metered supply flow ($CV_B + 0.5F$) exceeds normal volume losses (\dot{V}_{O_2} less \dot{V}_{CO_2} , \dot{V}_{sc} , $\dot{V}_{EB} = EV_B$), causing gas to be "pushed through" the exhaust bellows at the end of exhalation at the point where the main bellows reaches its top limit.

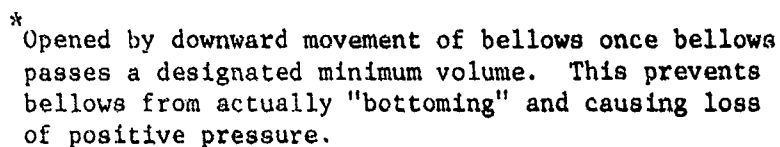
b. Determination of Transition from Push-through to Pull-through.

(1) At the point of perfect volume equilibrium

Σ volume inputs = Σ volume losses

$$\dot{V}_{EB} = EV_B \quad \dot{V}_s = CV_B = 0.5F$$

$$\dot{V}_{O_2} = BV_e \quad \dot{V}_{CO_2} = RBV_e \quad (1)$$



40

TABLE 1. DEFINITIONS OF SYMBOLS.

\dot{V}_B = Bellows displacement, liters per minute.

\dot{V}_e = Minute volume, liters per minute.

\dot{V}_{O_2} = Oxygen consumption, standard liters per minute.

\dot{V}_{CO_2} = CO_2 production, standard liters per minute.

B = $\dot{V}_{O_2} \div \dot{V}_e$

R = Respiratory quotient, $\dot{V}_{CO_2} \div \dot{V}_{O_2}$

E = Displacement ratio, exhaust bellows to main bellows.

C = Displacement ratio, supply bellows to main bellows.

F = Steady supply flow from all sources, standard liters per minute.

D = O_2 fraction in supply gas.

X = O_2 fraction in user's inspired gas.

Y = Value of minute volume at which the transition from pull-through to push-through occurs.

\dot{V}_{sc} = Volume lost in scrubber due to CO_2 absorption, standard liters per minute.

\dot{V}_{EB} = Flow out exhaust bellows, liters per minute.

\dot{V}_s = Supply flow from all sources.

\dot{V}_e is taken as \dot{V}_e , inspired.

$\dot{V}_{e, \text{ expired}} = \dot{V}_e (1 - B + RB)$

\dot{V}_T = Tidal volume.

$$\dot{V}_e, \text{ exp} = \dot{V}_e (1 - B + RB)$$

$$\dot{V}_B, \text{ exp} = \dot{V}_B, \text{ insp}, \text{ as bellows displacements must be exactly equal.}$$

The design objective in this case is to define the value of E, which will produce perfect volume equilibrium given all other appropriate parameters:

$$\text{now } \dot{V}_B, \text{ insp} = \dot{V}_B, \text{ exp}$$

$$\dot{V}_e, \text{ exp} = \dot{V}_e, \text{ insp} (1 - B + RB)$$

$$\text{where } \dot{V}_e \triangleq \dot{V}_e, \text{ insp}$$

The first step is to derive expressions for \dot{V}_B in terms of \dot{V}_e

(2) During exhalation, the liters of gas expired are the sum of the volume lost in CO_2 absorption, the flow out of the exhaust bellows, and the master bellows displacement, which can be expressed as:

$$\dot{V}_e, \text{ exp} = \dot{V}_{sc} + \dot{V}_{EB} + \dot{V}_B$$

$$\dot{V}_{sc} = (\dot{V}_e, \text{ exp} - E\dot{V}_B) (\% \text{ CO}_2 \text{ in expired gas})$$

$$\% \text{ CO}_2 = \frac{\dot{V}_{\text{CO}_2}}{\dot{V}_e, \text{ exp}} = \frac{RB\dot{V}_e}{\dot{V}_e (1 - B + RB)}$$

$$\therefore \dot{V}_{sc} = [\dot{V}_e (1 - B + RB) - E\dot{V}_B] \frac{RB}{(1 - B + RB)}$$

$$\dot{V}_{sc} = \dot{RBV}_e - \frac{\dot{RBEV}_B}{(1 - B + RB)} \quad (2)$$

$$\therefore \dot{V}_e (1 - B + RB) = \dot{RBV}_e - \frac{\dot{RBEV}_B}{(1 - B + RB)} + \dot{EV}_B + \dot{V}_B$$

$$\dot{V}_B (1 + E - \frac{RBE}{(1 - B + RB)}) = \dot{V}_e (1 - B + RB) - \dot{RBV}_e$$

$$\text{let } (1 - B + RB) = A$$

$$\frac{\dot{V}_B}{A} [1 + E (1 - \frac{RB}{A})] = \dot{V}_e (1 - \frac{RB}{A})$$

$$\dot{V}_B = \frac{\dot{AV}_e (1 - \frac{RB}{A})}{1 + E (1 - \frac{RB}{A})}$$

$$\dot{V}_B = \frac{\dot{AV}_e}{\frac{1}{(1 - \frac{RB}{A})} + E}$$

$$\frac{1}{1 - X} \approx 1 + X \text{ where } X \ll 1$$

$$\therefore \dot{V}_B \text{ exp} = \frac{\dot{AV}_e}{1 + \frac{RB}{A} + E} \quad (3)$$

$$\text{where } A = (1 - B + RB)$$

Equation (3) is valid at equilibrium. It is also valid during pull-through

(in pull-through, $\dot{V}_S > C\dot{V}_B + 0.5F$ and $\dot{V}_{EB} = E\dot{V}_B$).

(3) During inhalation:

$$\dot{V}_e = \dot{V}_B + \dot{V}_S$$

$$\dot{V}_e = \dot{V}_B + C\dot{V}_B + 0.5F$$

$$\dot{V}_{B, \text{ insp}} = \frac{\dot{V}_e - 0.5F}{1 + C} \quad (4)$$

Equation (4) is valid for equilibrium and for push-through (in push-through,

$\dot{V}_S = C\dot{V}_B + 0.5F$ and $\dot{V}_{EB} > E\dot{V}_B$).

(4) At equilibrium:

$$\dot{V}_{B, \text{ insp}} = \dot{V}_{B, \text{ exp}}$$

$$\dot{V}_{e, \text{ exp}} = \dot{V}_e (1 - B + RB) = \dot{V}_e (A)$$

From equation (3)

$$\dot{V}_e = \frac{\dot{V}_B}{A} \left(1 + \frac{RB}{A} + E \right)$$

From equation (4)

$$\dot{V}_e = \dot{V}_B (1 + C) + 0.5F$$

$$\therefore \dot{V}_B (1 + C) + 0.5F = \frac{\dot{V}_B}{A} \left(1 + \frac{RB}{A} + E\right)$$

Solve for E

$$\dot{V}_B (1 + C) + 0.5F - \frac{\dot{V}_B}{A} - \frac{RB\dot{V}_B}{A^2} = \frac{E}{A} \dot{V}_B$$

Simplify for $A = 1$

$$\dot{V}_B (1 + C - 1 - RB) + 0.5F = E\dot{V}_B$$

$$E = C - RB + \frac{0.5F}{\dot{V}_B}$$

$$\text{but, } \dot{V}_B = \frac{\dot{V}_e - 0.5F}{1 + C}$$

$$\therefore E = C - RB + \frac{0.5F(1 + C)}{\dot{V}_e - 0.5F} \quad (5)$$

Equation (5) may be used to size E based on other known parameters.

Equation (5) is called the equilibrium equation.

Equation (5) is strictly accurate only for $R = 1$. However, it is close enough for all cases where $R \neq 1$.

(5) The significance of equation (5) is as follows:

(a) Assume the apparatus is to be optimized for conditions of

$$\dot{V}_e = 40 \text{ lpm}$$

$$C = 0.09$$

$$R = 1.0$$

$$F = 1.0 \text{ lpm}$$

$$B = 0.04$$

(b) The appropriate value of E is 0.064.

(c) From equation (5), it can be seen that increasing the \dot{V}_e value at equilibrium results in a smaller E; e.g., as \dot{V}_e increases, a steadily smaller E is required to keep the system in volume equilibrium. The effect of this is:

o Let the optimization value of \dot{V}_e be Y.

o At $\dot{V}_e > Y$ gas is lost from the apparatus faster than it is supplied. The main bellows loses volume until it starts to bottom or activates the demand regulator at the end of inspiration. The situation is called "pull-through" because net exhaust flow exceeds the metered supply flow and gas is literally pulled through the system by the pumping action of the exhaust bellows.

o At $\dot{V}_e < Y$, the metered supply flow, $\dot{V}_s = C\dot{V}_B + 0.5F$, exceeds the rate at which volume is lost from the system. The main bellows steadily gains volume until it tops out at the end of each exhalation and some gas is forced through the exhaust bellows and out the relief valve. This situation is called "push-through".

c. pO_2 Performance in a Pull-through Mode.

(1) Valid equations.

$$\dot{V}_e > Y$$

$$\dot{V}_{EB} = E\dot{V}_B$$

$$\dot{V}_B, \text{ exp} = \frac{\dot{V}_e, \text{ exp}}{1 + \frac{RB}{A} + E} = \frac{A\dot{V}_e}{1 + \frac{RB}{A} + E}$$

Oxygen conservation:

$$D\dot{V}_s = \dot{V}_{O_2} + (X - B) \dot{V}_{EB}$$

Volume conservation:

$$\dot{V}_s = \dot{V}_e - \dot{V}_B$$

(2) Inspired pO_2 and supply flow.

$$\dot{V}_e - \dot{V}_B = B\dot{V}_e + (X - B) E\dot{V}_B$$

This rearranges to

$$X = \frac{D - B}{E} \left(\frac{\dot{V}_e}{\dot{V}_B} \right) - \frac{D}{E} + B$$

however, from equation (3)

$$\frac{\dot{V}_e}{\dot{V}_B} = \frac{1 + \frac{RB}{A} + E}{A}$$

∴ For $\dot{V}_e > Y$

$$X = \left(\frac{D - B}{E} \right) \left(\frac{1 + \frac{RB}{A} + E}{A} \right) - \frac{D}{E} + B \quad (6)$$

Note: X is independent of \dot{V}_e and $A = (1 - B + RB)$

(3) Supply flow.

$$\dot{V}_s = \dot{V}_e - \dot{V}_B$$

$$= \dot{V}_e - \frac{\dot{V}_e}{1 + RB + E}, \text{ using equation (3)}$$

$$\dot{V}_s = \dot{V}_e \frac{(RB + E)}{1 + RB + E} \quad (7)$$

Valid when $\dot{V}_e > Y$

d. pO_2 Performance in a Push-through Mode.

(1) Valid equations. Oxygen conservation:

$$\dot{DV}_s = \dot{V}_{O_2} + (X - B) \dot{V}_{EB}$$

$$\dot{V}_s = C\dot{V}_B + 0.5F$$

$$\dot{V}_{EB} > E\dot{V}_B$$

From equation (4)
$$\dot{V}_B = \frac{\dot{V}_e - 0.5F}{1 + C}$$

Volume conservation:

$$\dot{V}_{EB} = \dot{V}_s - \dot{V}_{sc} \quad (\text{assuming } R = 1)$$

$$\dot{V}_{e, \text{exp}} = \dot{V}_e (1 - B + RB)$$

(2) Inspired pO_2 and supply flow. Volume conservation:

$$\dot{V}_{EB} + \dot{V}_{sc} + B\dot{V}_e = \dot{V}_s + RB\dot{V}_e$$

From equation (2)

$$\dot{V}_{sc} = RB \left(\dot{V}_e - \frac{\dot{V}_{EB}}{A} \right)$$

$$\begin{aligned}\dot{V}_{EB} &= \dot{V}_s + R\dot{V}_e - \dot{V}_{sc} - B\dot{V}_e \\ &= \dot{V}_s + R\dot{V}_e - R\dot{V}_e + \frac{R\dot{V}_e}{A} - B\dot{V}_e\end{aligned}$$

$$\dot{V}_{EB} = \frac{\dot{V}_s - B\dot{V}_e}{1 - \frac{RB}{A}}$$

Supply flow:

$$\dot{V}_s = C\dot{V}_B + 0.5F$$

$$\dot{V}_s = C \left(\frac{\dot{V}_e - 0.5F}{1 + C} \right) + 0.5F$$

Inspired pO_2 :

$$D\dot{V}_s = B\dot{V}_e + (X - B)\dot{V}_{EB}$$

$$X = D \left(\frac{\dot{V}_s}{\dot{V}_{EB}} \right) + B \left(1 - \frac{\dot{V}_e}{\dot{V}_{EB}} \right)$$

$$\dot{V}_s = C \left(\frac{\dot{V}_e - 0.5F}{1 + C} \right) + 0.5F \quad (8)$$

$$\dot{V}_{EB} = \frac{\dot{V}_s - B\dot{V}_e}{1 - \frac{RB}{A}} \quad (9)$$

where $A = 1 - B + RB$

$$X = D \frac{\dot{V}_s}{\dot{V}_{EB}} + B \left(1 - \frac{\dot{V}_e}{\dot{V}_{EB}}\right) \quad (10)$$

Equations 8, 9, and 10 (push-through equations) are valid for $\dot{V}_e < Y$.

e. CO_2 Absorbent Canister Design

(1) Design CO_2 Loading. Assumptions:

Average Respiratory Minute Volume (RMV) = 40 lpm

Average CO_2 Production = 1.6 slpm

(2) Required Absorbent.

$$\begin{aligned} (a) \quad & 1.6 \text{ slpm} \times 120 \text{ min} \times \frac{1 \text{ ft}^3}{28.32 \text{ l}} \times \frac{0.11429 \text{ lb CO}_2}{\text{ft}^3} \\ & = 0.78 \text{ lb CO}_2 \end{aligned}$$

(b) From Bentz (1976). In high relative humidity (RH) situations for Sodasorb[®], at 70°F

$$\frac{\text{Actual Life}}{\text{Theoretical Life (at 600 fsw)}} = 0.72 \text{ to } 0.82, \text{ vertical bed}$$

$$= 0.75, \text{ annular bed}$$

$$= 0.35\text{--}0.65, \text{ horizontal bed}$$

$$\text{Theoretical Life} = \frac{0.41 \text{ lb CO}_2}{\text{lb absorbent}}$$

$$\therefore \text{Absorption range}^* = (0.7\text{--}0.8) (0.41)$$

$$= 0.29 \text{ to } 0.33 \frac{\text{lb CO}_2}{\text{lb chemical}}$$

$$\text{Density of Sodasorb}^\circ \text{ HP (high performance)} = 0.031 \text{ lb/in}^3$$

$$\text{Required chemical} = \frac{0.78 \text{ lb CO}_2}{\frac{0.30 \text{ lb CO}_2}{\text{lb chemical}}} = 2.60 \text{ lb}$$

$$\text{Required Volume} = \frac{2.60 \text{ lb}}{0.031 \text{ lb/in}^3} = 83.9 \text{ in}^3$$

*Annular or vertical bed geometry. Prototype design uses a bed where the flow is vertical by downward.

(c) Design initially for 2.75 lb absorbent (88.6 in³).

NOTE: Diving industry rule of thumb says 0.2 lb CO₂/lb chemical absorption is a safe design rule for Sodasorb[®]. Sodasorb[®] HP is more efficient and a design absorption level of 0.30 lb CO₂/lb chemical is considered good practice.

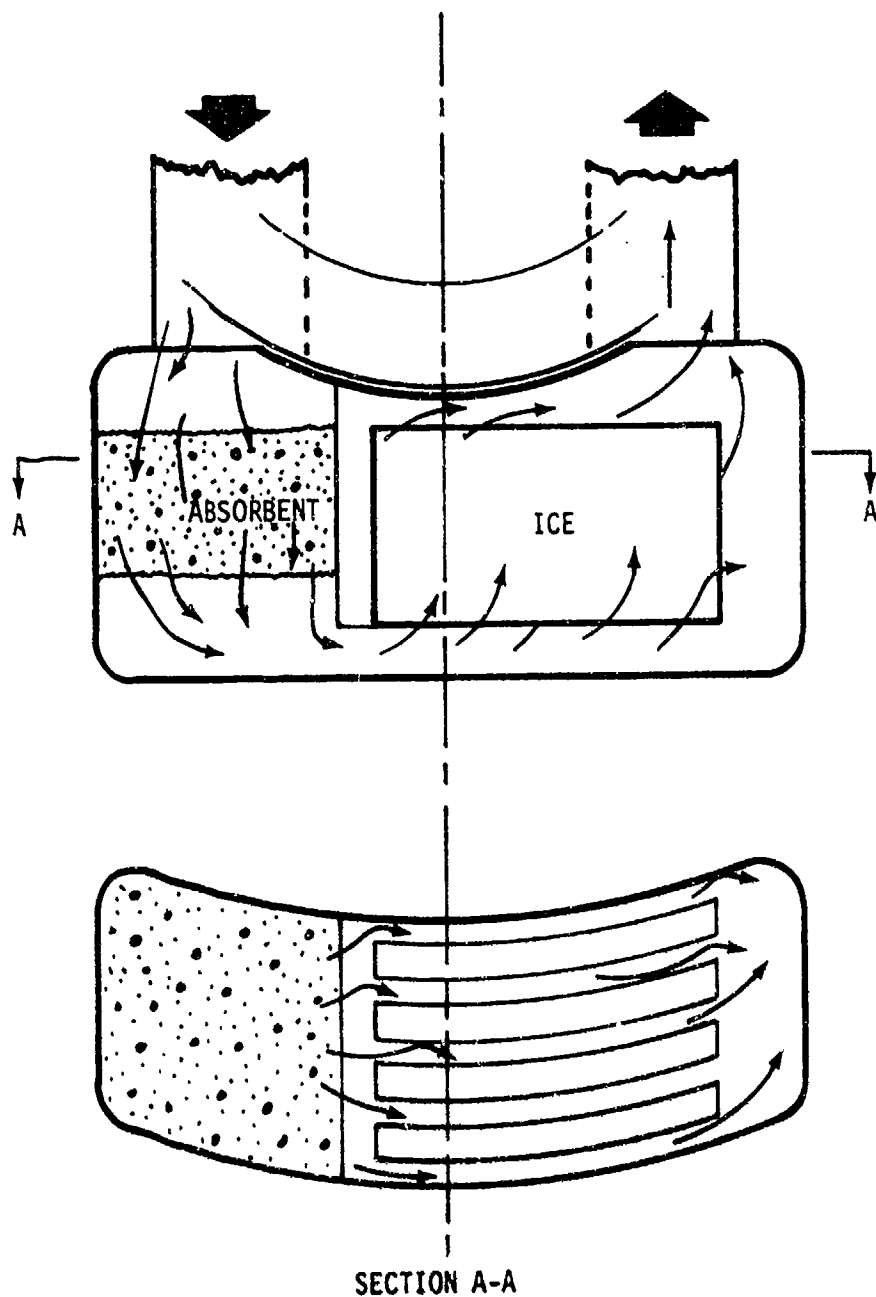


Figure 19. Design Concept "A" for Gas Scrubbing/Cooling.

(3) Bed Design.

(a) From Appendix A, the most appropriate pressure drop equation appears to be

$$\Delta P \text{ (cm H}_2\text{O)} = 0.363L \left(\frac{F}{A} \right)^{1.25}$$

where L = path length parallel to gas flow, cm

F = gas flow rate, lpm

A = cross sectional area perpendicular to flow, cm²

(b) Two bed design concepts were considered: A (Figure 19) and B (Figure 20). Absorbent canister parameters appear in Table 2.

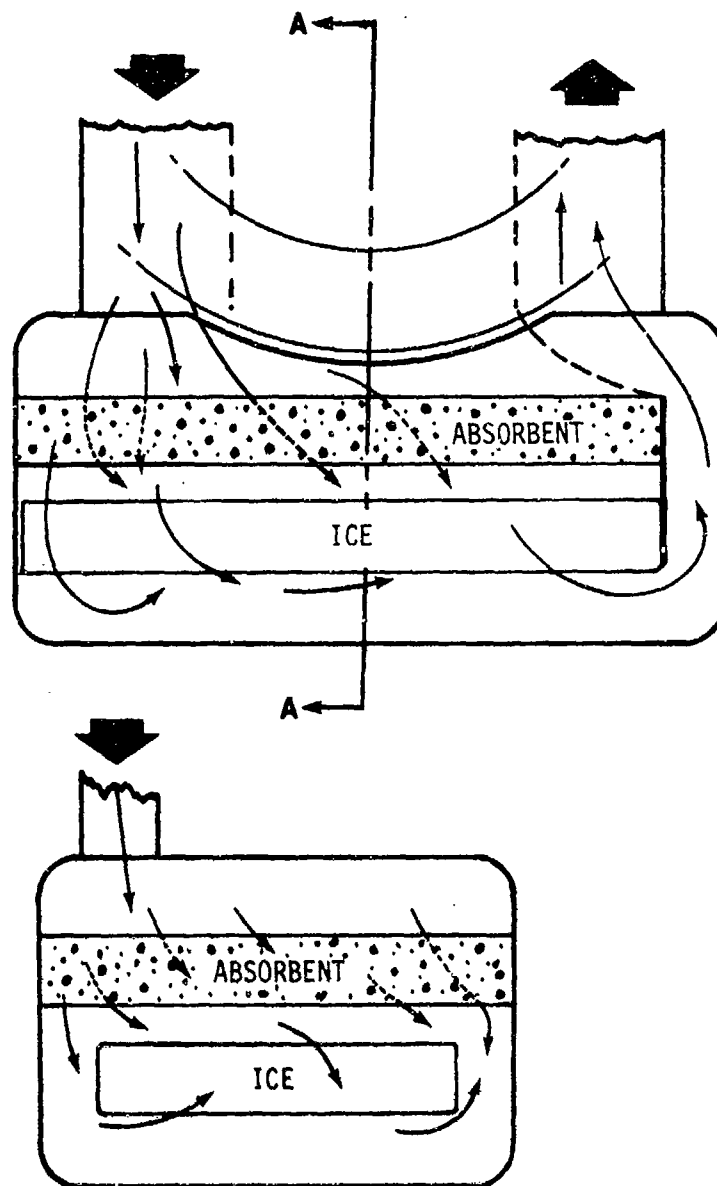
	<u>Bed A</u>	<u>Bed B</u>
Length	8.0 cm	3.5 cm
Area	194.0 cm ²	468.0 cm ²
ΔP at F = 300 lpm	5.01 cm H ₂ O	0.73 cm H ₂ O
Volume	1552.0 cm ³	1638.0 cm ³
Absorbent Capacity	2.94 lb	3.10 lb

Bed B is obviously superior when looked at in isolation, however, use of Bed A permits a simpler duct system.

(4) Bed Weight. Assumptions:

Periphery of bed covered with 0.060-inch plastic of specific gravity.

Faces covered with 0.030-inch stainless steel with a void area of 50 percent.



SECTION A-A

Figure 20. Design Concept "B" for Gas Scrubbing/Cooling.

TABLE 2. ABSORBENT CANISTER PARAMETERS.

	<u>Bed A</u>	<u>Bed B</u>
Periphery	55.8 cm	92.4 cm
Length	8.0 cm	3.62 cm
Peripheral Area	446.4 cm ²	334.5 cm ²
Face Area	388.0 cm ²	936.0 cm ²
Housing Volume	39.1 in ³	48.9 in ³
Housing Weight	1.41 lb	1.77 lb
Closure Weight	0.4 lb	0.3 lb
Total Housing Weight	1.81 lb	2.07 lb

f. Coolant Canister Design.

(1) Design Requirement. The coolant canister must provide 400 Btu of cooling over a two-hour period.

(2) Coolant Media. Appendix B contains a detailed analysis of respirator cooling and lists the various chemicals that were investigated as potential coolants. Ice was selected because of its simplicity, safety, and relatively high cooling capacity per pound, 180 Btu/lb from ice at 32°F to liquid water at 70°F. Solid ammonia and solid CO₂ present potentially higher cooling capacities per pound; however, their gaseous residue is troublesome and the necessary heat exchangers, containers, and venting mechanisms would cause the overall assembly to be heavier than the ice canister selected.

(3) Canister Design. The canister design concepts are illustrated in Figures 19 and 20.

(4) Coolant Canister Weight. Coolant canister weight for each of the designs offered is approximately:

2.8 lb water

0.4 lb container

3.2 lb total

(5) Heat Transfer Rate.

(a) Both canister designs are designed to transfer approximately 4.2 Btu/min with conditions as follows:

Inlet air conditions: 130°F dry bulb, 65 percent RH

Average flow rate: 40 lpm

(b) Total coolant capacity is 500 Btu, 25 percent in excess of design requirements.

g. Gas Supply Requirements.

(1) Design Requirements. The gas supply system outlined above in paragraph 2.a., e.g.,

$$\dot{V}_g = C \dot{V}_B + 0.5F, \text{ with } C = 0.09, F = 1.0$$

may also be written as

$$\dot{V}_g = \frac{C}{1+C} \dot{V}_B + 0.5F$$

The 120-minute average \dot{V}_e is taken as 40 lpm.

∴ The design value of \dot{V}_s is

$$\dot{V}_s = \frac{0.09}{1.09} 40 + 0.5 (1.0) = 3.803 \text{ lpm}$$

(2) Gas Supply Cylinder Capacity Requirements.

The 120-minute gas requirement is $(120)(3.803) = 456.4 \text{ l}$

$$456.4 \text{ l} \times \frac{1 \text{ ft}^3}{28.32 \text{ l}} = 16.1 \text{ scf}$$

deliverable at 100 psig

(3) Selected Cylinder.

(a) The gas cylinder selected for use in the prototype SCBA is a Luxfer L21W. Cylinder capacity is 21 scf @ 3000 psig.

∴ $21 \times \frac{2900}{3000} = 20.3 \text{ scf}$ is deliverable at 100 psig, well in excess of the 16.1 scf expected to be required.

(b) Cylinder weight is 5.5 pounds.

(4) Computer Simulation. A gas consumption program (labeled AFTST) was developed to permit any given history of respiratory demand to be modeled. Table 3 shows the results appropriate for a 180-pound man performing a Man Test 4 per NIOSH regulations (30 CFR11, subpart H). Under those conditions, gas consumption over a two-hour period would be about 14.9 scf, well under the 20.3 scf available.

TABLE 3. SCBA BREATHING PROFILE.

AIR FORCE IMPROVED BREATHING APPARATUS TEST

PRESSURE= 1.00 ATM., ORIFICE= 1.000 LITERS/MIN; BYPASS= 0.000 LITERS/MIN.

BELLows SUPPLY/MAIN RATIO= 0.0000, EXHAUST/MAIN= 0.0040, VOLUME MIN= 2.000, MAX= 6.000 LITERS

% O2 SUPPLY= 60.00, SCRUBER EFFICIENCY= 97.00 %; RG= 1.000

TEST TIME (MIN)	CONTROLLED VARIABLES			INSPIRED		O2		GAS USED	CO2 ABSORBED		MAIN BELLows	
	RPM	RW (LITER)	XO2 OF RW	PO2 (ATM)	PCO2 (ATM)	(STD LITERS/MIN) SUPPLY	EXHAUST	(LITERS) TOTAL	PER MIN	TOTAL	VOLUME AT END OF INHALE	EXHALE
1 0	8.7	8.75	4.000	0.5837	0.00077	0.7290	0.5128	1.215	0.3180	0.318	5.1350	6.0000
2 0	8.7	8.75	4.000	0.5678	0.00103	0.7290	0.4849	2.430	0.3220	0.640	5.1350	6.0000
3 0	16.0	31.50	4.000	0.5136	0.00116	1.8358	0.9555	5.490	1.1322	1.822	4.2226	6.0000
4 0	16.0	31.50	4.000	0.4722	0.00116	1.8358	0.8624	8.549	1.1827	3.005	4.2226	6.0000
5 0	33.0	167.00	4.000	0.3658	0.00117	5.5261	2.3635	17.759	4.0261	7.031	2.1408	5.0735
6 0	16.0	31.50	4.000	0.3610	0.00116	1.8385	0.5907	20.824	1.1849	8.216	3.3441	5.1248
7 0	16.0	31.50	4.000	0.3570	0.00116	1.8385	0.5815	23.888	1.1849	9.401	3.3954	5.1761
8 0	23.0	46.00	4.000	0.3442	0.00117	2.5468	0.8309	28.133	1.7305	11.131	3.2306	5.0396
9 0	23.0	46.00	4.000	0.3365	0.00117	2.5468	0.8038	32.377	1.7306	12.862	3.0941	4.9030
10 0	23.0	46.00	4.000	0.3315	0.00117	2.5468	0.7862	33.622	1.7306	14.592	2.9575	4.7667
11 0	23.0	46.00	4.000	0.3283	0.00117	2.5468	0.7750	40.867	1.7306	16.323	2.8210	4.6300
12 0	23.0	46.00	4.000	0.3263	0.00117	2.5468	0.7679	45.112	1.7306	18.054	2.6845	4.4935
13 0	16.0	31.50	4.000	0.3204	0.00116	1.8385	0.5272	48.176	1.1849	19.238	2.7640	4.5448
14 0	16.0	31.50	4.000	0.3376	0.00116	1.8385	0.5379	51.240	1.1849	20.423	2.8153	4.5961
15 0	16.0	31.50	4.000	0.3404	0.00116	1.8385	0.5437	54.304	1.1849	21.608	2.8666	4.6473
16 0	14.0	28.75	4.000	0.3443	0.00116	1.7042	0.5010	57.145	1.0814	22.689	2.8768	4.7342
17 0	14.0	28.75	4.000	0.3468	0.00116	1.7042	0.5063	59.985	1.0814	23.771	2.9637	4.8211
18 0	14.0	28.75	4.000	0.3486	0.00116	1.7042	0.5100	62.826	1.0814	24.852	3.0506	4.9080
19 0	14.0	28.75	4.000	0.3499	0.00116	1.7042	0.5127	65.666	1.0814	25.933	3.1375	4.9949
20 0	14.0	28.75	4.000	0.3508	0.00116	1.7042	0.5145	68.507	1.0814	27.015	3.2243	5.0818
21 0	14.0	28.75	4.000	0.3514	0.00116	1.7042	0.5159	71.348	1.0814	28.096	3.3112	5.1687
22 0	14.0	28.75	4.000	0.3519	0.00116	1.7042	0.5168	74.188	1.0814	29.178	3.3981	5.2556
23 0	14.0	28.75	4.000	0.3522	0.00116	1.7042	0.5175	77.029	1.0814	30.259	3.4850	5.3425
24 0	14.0	28.75	4.000	0.3525	0.00116	1.7042	0.5180	79.869	1.0814	31.340	3.5719	5.4294
25 0	14.0	28.75	4.000	0.3526	0.00116	1.7042	0.5184	82.710	1.0814	32.422	3.6588	5.5163
26 0	14.0	28.75	4.000	0.3528	0.00116	1.7042	0.5187	85.550	1.0814	33.503	3.7457	5.6031
27 0	8.7	8.75	4.000	0.3735	0.00111	0.7482	0.1589	86.797	0.3381	33.841	5.0644	5.9509
28 0	8.7	8.75	4.000	0.3833	0.00111	0.7312	0.2820	88.016	0.3251	34.166	5.1350	6.0000
29 0	16.0	31.50	4.000	0.3683	0.00116	1.8358	0.6260	91.075	1.1827	35.349	4.2226	6.0000
30 0	16.0	31.50	4.000	0.3630	0.00116	1.8358	0.6128	94.135	1.1827	36.532	4.2226	6.0000
31 0	16.0	31.50	4.000	0.3590	0.00116	1.8358	0.6036	97.195	1.1827	37.715	4.2226	6.0000
32 0	16.0	31.50	4.000	0.3559	0.00116	1.8358	0.5967	100.254	1.1827	38.898	4.2226	6.0000
33 0	33.0	167.00	4.000	0.3264	0.00117	4.3187	1.4455	107.464	3.0866	41.934	3.1377	5.3934
34 0	19.0	38.25	4.000	0.3296	0.00116	2.1682	0.6393	111.068	1.4389	43.433	3.5364	5.3573
35 0	19.0	38.25	4.000	0.3310	0.00116	2.1682	0.6432	114.681	1.4389	44.872	3.6002	5.3211
36 0	19.0	38.25	4.000	0.3320	0.00116	2.1682	0.6459	118.295	1.4389	46.311	3.6641	5.2850
37 0	19.0	38.25	4.000	0.3327	0.00116	2.1682	0.6478	121.909	1.4389	47.750	3.7279	5.2488
38 0	19.0	38.25	4.000	0.3331	0.00116	2.1682	0.6491	125.523	1.4389	49.189	3.7918	5.2127
39 0	19.0	38.25	4.000	0.3334	0.00116	2.1682	0.6500	129.137	1.4389	50.627	3.8556	5.1766
40 0	19.0	38.25	4.000	0.3337	0.00116	2.1682	0.6506	132.750	1.4389	52.066	3.9195	5.1404
41 0	19.0	38.25	4.000	0.3338	0.00116	2.1682	0.6510	136.364	1.4389	53.505	3.9833	5.1042
42 0	19.0	38.25	4.000	0.3339	0.00116	2.1682	0.6513	139.978	1.4389	54.944	4.0472	5.0681
43 0	23.0	46.00	4.000	0.3298	0.00117	2.5468	0.7798	144.223	1.7305	56.675	3.1226	4.9316
44 0	23.0	46.00	4.000	0.3273	0.00117	2.5468	0.7713	148.468	1.7306	58.405	2.9061	4.7950
45 0	23.0	46.00	4.000	0.3258	0.00117	2.5468	0.7658	152.712	1.7306	60.136	2.8495	4.6586
46 0	8.7	8.75	4.000	0.3646	0.00111	0.7482	0.1470	153.959	0.3381	60.474	4.1099	5.0143
47 0	8.7	8.75	4.000	0.3690	0.00111	0.7482	0.1569	155.206	0.3381	60.812	4.4686	5.3701
48 0	16.0	31.50	4.000	0.3569	0.00116	1.8385	0.5212	158.270	1.1849	61.997	3.6407	5.4214
49 0	16.0	31.50	4.000	0.3542	0.00116	1.8385	0.5750	161.335	1.1849	63.181	3.6920	5.4727
50 0	16.0	31.50	4.000	0.3522	0.00116	1.8385	0.5785	164.399	1.1849	64.366	3.7433	5.5240
51 0	16.0	31.50	4.000	0.3507	0.00116	1.8385	0.5673	167.463	1.1849	65.551	3.7945	5.5753
52 0	16.0	31.50	4.000	0.3497	0.00116	1.8385	0.5649	170.527	1.1849	66.736	3.8458	5.6266
53 0	16.0	31.50	4.000	0.3489	0.00116	1.8385	0.5632	173.592	1.1849	67.921	3.8971	5.6778
54 0	23.0	46.00	4.000	0.3397	0.00117	2.5468	0.8130	177.836	1.7305	69.651	3.7323	5.5413
55 0	23.0	46.00	4.000	0.3341	0.00117	2.5468	0.7945	182.081	1.7306	71.382	3.5958	5.4048
56 0	23.0	46.00	4.000	0.3303	0.00117	2.5468	0.7814	186.326	1.7306	73.112	3.4593	5.2683
57 0	23.0	46.00	4.000	0.3278	0.00117	2.5468	0.7728	190.571	1.7306	74.843	3.3228	5.1318
58 0	23.0	46.00	4.000	0.3262	0.00117	2.5468	0.7679	194.815	1.7306	76.573	3.1863	4.9952
59 0	25.0	61.75	4.000	0.3223	0.00117	2.8276	0.8556	198.528	1.9469	78.520	2.9120	4.7843
60 0	25.0	61.75	4.000	0.3201	0.00117	2.8276	0.8456	204.241	1.9469	80.468	2.7010	4.5733
61 0	25.0	61.75	4.000	0.3188	0.00117	2.8276	0.8410	208.953	1.9469	82.416	2.4901	4.3624
62 0	8.7	8.75	4.000	0.3502	0.00111	0.7482	0.1441	210.200	0.3381	82.753	3.8136	4.7182
63 0	8.7	8.75	4.000	0.3561	0.00111	0.7482	0.1539	211.447	0.3381	83.091	4.1694	5.0740

h. Materials and Weight.

(1) Phase 1.

(a) Technical Requirements. The SCBA is required to weigh no more than 30 pounds when fully charged for operational use, and to be fabricated in the smallest size possible, while utilizing commercially available system components, such as tubing, valves, cylinders, etc. The materials, components, and assemblies must survive in a CBR environment without degradation of specified SCBA performance characteristics. In addition to the above requirements, the materials forming the breathing circuit must be nontoxic to humans and compatible with cleaning/disinfecting chemicals approved for use with life support apparatus.

(b) Critical Materials, Components, and Overall Weight. The Phase I design analysis considered the materials and components itemized in Table 4 as critical from the standpoints of the material and weight requirements, as well as meeting the overall performance objectives. The individual weight for each of these items is also listed in Table 4.

(c) Miscellaneous Components. Those components necessary to complete the SCBA top assembly design, but not considered to be of a critical nature, are itemized in Table 5. The weight for each miscellaneous component is also listed.

(d) Weight Summary. The estimated weight summary for the Phase I SCBA design is given in Table 6.

TABLE 4. CRITICAL MATERIALS AND COMPONENTS.

<u>COMPONENT</u>	<u>MATERIAL</u>	<u>VENDOR</u>	<u>WEIGHT (LB)</u>
Gas Flask	Filament Reinforced Aluminum	Luxfer L21W	5.50
CO ₂ Absorbent	Sodasorb® HP	Dewey & Almey	3.10
Absorbent Canister	HIP (high impact plastic)	N/A	2.70
Coolant and Housing	Ice in Polyethylene	N/A	3.20
HP Gas Regulator	Brass	Emerson 9S-03-D401S	1.25
LP Gas Regulator	Plastic	Sierra Engineering	0.25
Main Bellows	0.010 Estare	Gagne Associates	0.31
Supply and Exhaust Bellows	0.010 Estane	Gagne Associates	0.08
Tilt Valve Assembly	Various	Scott	0.3
Mouthpiece Assembly	Plastic	Koegel Y Valve	0.19
Main Bellows Spring Assembly	Various	John Evans R315	0.5
			<hr/> 17.38

TABLE 5. MISCELLANEOUS COMPONENTS.

<u>COMPONENT</u>	<u>MATERIAL</u>	<u>WEIGHT (LB)</u>
Main bellows cover	HIP, 0.060	0.30
Relief valve	Various	0.12
Back plate	HIP, 0.010	0.66
Bottom main bellows clamp	HIP, variable	0.31
Ducting on back plate	HIP, 0.060	0.41
Housing for absorbent canister and ice pack	HIP, 0.060	2.0
Supply tube from LP regulator	HIP, 0.040	0.04
Bracing and bottle supports	Various	1.33
One-way valves and holders for supply and exhaust bellows	HIP, neoprene	0.34
Hoses		0.24
Harness straps	Fabric	0.20
Buckles	Metal	0.23
Outer cover	HIP, 0.060	0.76
Miscellaneous fasteners		<u>2.00</u> 8.94

TABLE 6. WEIGHT SUMMARY.

Critical materials	17.38 lb
Miscellaneous materials	<u>8.94 lb</u>
Total identified materials	26.32 lb
Plus 20% allowance on miscellaneous items	<u>1.79 lb</u>
Total estimated weight	28.11 lb

(2) Phase II.

(a) Materials. The SCBA constructed in Phase II does not, in some cases, contain components fabricated from materials determined in Phase I to be the optimum from a weight standpoint. The majority of these deviations are in the structural assembly. The Phase I effort recommended the back plate (frame), ducting on the back plate, and the CO₂ absorbent and gas cooler canisters be fabricated from high impact plastic (HIP). These parts (frame, supply and exhaust ducts, supply bellows and exhaust bellows ducts), as shown in Figures 11 and 12, and the gas cooler canister and spacer plates (illustrated in Figure 9) are fabricated from aluminum rather than HIP. The CO₂ absorbent canister illustrated in Figure 9 is fabricated from stainless steel rather than HIP. These deviations from the Phase I design analysis were considered necessary, because of the lead times required for the tooling to fabricate these parts from HIP and the excessive tooling cost for fabricating only one unit. The engineering drawing package prepared during Phase II documents the Phase II SCBA, as built, using aluminum for the structural parts, rather than HIP. Optimization of materials should be accomplished during the preproduction prototype design after USAF testing of the Phase II SCBA.

(b) Weight. The SCBA developed during Phase II weighs 34.0 pounds fully charged. The design requirement was a maximum weight of 30 pounds fully charged.

1. Pressure Drop Computer Modeling.

(1) Computer Program. The Phase I design analysis considered two

basic SCBA designs which differed essentially on the design and arrangement of the CO₂ absorbent canister and the gas cooler. These design concepts, designated A (absorbent and cooler canisters side by side) and B (absorbent canister above cooler), are illustrated in Figures 19 and 20, respectively.

The flow resistance of each design concept was modeled on a Reimers Consultants' computer. The flow path model used is illustrated in Figure 21. Table 7 lists the pressure drop equation used for each of the flow path elements, plus all of the other input values pertinent to the program for Design Concept A. Table 8 lists the same data for Design Concept B.

A computer simulated breathing resistance test was conducted for each design concept at breathing flow rates of 200, 300, 400, and 350 lpm.

(2) Results. The results of the computer simulations are listed in Table 9. The computer program assumes a sine-wave breathing pattern. At these \dot{V}_e , actual wave forms would be flattened somewhat with a ratio of peak flow to minute volume of about 2.7. That ratio in sine-wave flow is 3.14. Thus, the peak flows given will be appropriate in service to \dot{V}_e values about 16 percent greater than indicated. The bellows spring force, listed as item 17 in Tables 7 and 8, was set to produce a static positive pressure of 1.5 inches water, the maximum level permitted under NIOSH regulations (30 CFR 11, Part 11.85-6(d)). Copies of computer runs from which the data in Table 9 were taken are contained in Appendix C.

The diagram illustrates a vacuum system for a gas turbine engine. The main components and their connections are as follows:

- Supply Bellows:** Connected to the system at point B.
- Main Bellows:** Connected to the system at point A.
- Exhaust Bellows:** Connected to the system at point C.
- Valves:** The system includes several valves labeled 6, 16, and 19.
- Flow Path:** The flow starts from the Supply Bellows (B) through a vertical pipe (7) and a valve (6) into the Main Bellows (A). From the Main Bellows (A), the flow goes through a horizontal pipe (5) and a valve (16) into the Exhaust Bellows. The Exhaust Bellows are connected to a turbine engine (19) via a pipe (18) and a valve (17).
- Other Components:** The system also includes a Cooler (13) and a Scrubber (11) connected to the main flow line. A pressure gauge (15) is located near the Exhaust Bellows. A vertical pipe (14) with a valve (12) connects the main flow line to the Cooler and Scrubber. A horizontal pipe (3) with a valve (4) and a pressure gauge (8) is also shown. A vertical pipe (9) with a valve (10) connects the main flow line to the Exhaust Bellows.

Figure 21. Flow Path Key For Air Force Δ^P Program (AFDP).

TABLE 7. INPUT INFORMATION FOR DESIGN A, SCRUBBER AND COOLER SIDE-BY-SIDE.

INPUT NO.	FLOW ELEMENT	LIST NO.	AP DATA		
			D_1	D_2	D_3
1.	Mouthpiece	1	0.0	0.000000793	2.0
2.	Mouthpiece check valve	2,8	0.427	0.000003172	2.0
3.	Hose to/from mouthpiece	3,9	0.0	0.000000565	2.0
4.	Duct from main bellows	4	0.0	0.000009108	2.0
5.	Main bellows outlet	5	0.0	0.000007014	2.0
6.	Bellows flapper valve	6,16,17	0.5	0.00000820	2.0
7.	Duct to scrubber	10	0.0	0.00001097	2.0
8.	Gas supply duct	7	0.0	0.000018718	2.0
9.	Scrubber	11	0.0	0.004	1.25
10.	Duct to cooler	12	0.0	0.000001505	2.0
11.	Duct to exhaust bellows	15	0.0	0.000002295	2.0
12.	Cooler	13	0.0	0.000000391	2.0
13.	Duct to main bellows	14	0.0	0.000006859	2.0
14.	Exhaust duct	18	0.0	0.000002041	2.0
15.	Exhaust valve	19	7.0	0.0000625	2.0
16.	Duct from supply bellows	20	0.0	0.000001488	2.0

			UNIT OF MEASURE		QUANTITY
17.	Bellows force-constant		(grams)		2781
18.	Bellows spring rate		(grams/liter bellows volume)		10.0
19.	Bellows spring zero volume		(liters bellows volume)		3.0
20.	Main bellows volume-maximum		(liters)		6.0
21.	Main bellows volume-minimum		(liters)		2.0
22.	Main bellows end area		(cm ²)		730

TABLE 7. INPUT INFORMATION FOR DESIGN A, SCRUBBER AND COOLER SIDE-BY-SIDE
(CONCLUDED).

<u>INPUT NO.</u>	<u>FLOW ELEMENT</u>	<u>UNIT OF MEASURE</u>	<u>QUANTITY</u>
23.	Supply/main bellows volume		0.09
24.	Exhaust/main bellows volume		0.064
25.	RMV	(liters/minute)	See Table 9
26.	BPM	(minute ⁻¹)	See Table 9
27.	Constant flow rate total	(liters/minute)	1.0
28.	Supply demand valve setting	(cm H ₂ O below 1 atmos.)	2.0
29.	Initial main bellows volume	(liters)	5.5
30.	Number of increments/breath	- (maximum 200)	50

NOTE: Items 1 to 16 in the form $\Delta P \text{ (cm H}_2\text{O)} = (D_1 + D_2)^{D_3}$

TABLE 8. INPUT INFORMATION FOR DESIGN B, SCRUBBER ABOVE COOLER.

INPUT NO.	FLOW ELEMENT	LIST NO.	<u>ΔP DATA</u>		
			<u>D₁</u>	<u>D₂</u>	<u>D₃</u>
1.	Mouthpiece	1	0.0	0.000000793	2.000
2.	Mouthpiece check valve	2,8	0.427	0.000003172	2.000
3.	Hose to/from mouthpiece	3,9	0.0	0.000000565	2.000
4.	Duct from main bellows	4	0.0	0.000003059	2.000
5.	Main bellows outlet	5	0.0	0.000007014	2.000
6.	Bellows flapper valve	6,16,17	0.5	0.0000082	2.000
7.	Duct to scrubber	10	0.0	0.00000672	2.000
8.	Gas supply duct	7	0.0	0.00007009	2.000
9.	Scrubber	11	0.0	0.0005986	1.25
10.	Duct to cooler	12	0.0	0.000002256	2.0
11.	Duct to exhaust bellows	15	0.0	0.000002295	2.0
12.	Cooler	13	0.0	0.000001978	2.0
13.	Duct to main bellows	14	0.0	0.000003349	2.0
14.	Exhaust duct	18	0.0	0.000002041	2.0
15.	Exhaust valve	19	7.0	0.0000624	2.0
16.	Duct from supply bellows	20	0.0	0.000001488	2.0

		<u>UNIT OF MEASURE</u>		<u>QUANTITY</u>	
17.	Bellows force-constant	(grams)		2781	
18.	Bellows spring rate	(grams/liter bellows volume)		10.0	
19.	Bellows spring zero volume	(liters bellows volume)		3.0	
20.	Main bellows volume-maximum	(liters)		6.0	
21.	Main bellows volume-minimum	(liters)		2.0	
22.	Main bellows end area	(cm ²)		730	

TABLE 8. INPUT INFORMATION FOR DESIGN B, SCRUBBER ABOVE COOLER (CONCLUDED).

<u>INPUT NO.</u>	<u>FLOW ELEMENT</u>	<u>UNIT OF MEASURE</u>	<u>QUANTITY</u>
23.	Supply/main bellows volume		0.09
24.	Exhaust/main bellows volume		0.064
25.	RMV	(liters/minute)	See Table 9
26.	BPM	(minute ⁻¹)	See Table 9
27.	Constant flow rate total	(liters/minute)	1.0
28.	Supply demand valve setting	(cm H ₂ O below 1 atmos.)	2.0
29.	Initial main bellows volume	(liters)	5.5
30.	Number of increments/breath	- (maximum 200)	50

NOTE: Items 1 to 16 in the form $\Delta P \text{ (cm H}_2\text{O)} = (D_1 + D_2)^{D_3}$

TABLE 9. RESULTS OF COMPUTER SIMULATED BREATHING RESISTANCE TESTS.

\dot{V}_e (lpm)	FREQ. (BPM)	V_T (l)	PEAK FLOW (lpm)	DESIGN A		DESIGN B	
				EXPIRATION PEAK (cm H ₂ O)	INSPIRATION PEAK (cm H ₂ O)	EXPIRATION PEAK (cm H ₂ O)	INSPIRATION PEAK (cm H ₂ O)
63.69	25.47	2.5	200	7.91	1.86	5.51	2.10
95.54	31.85	3.0	300	10.97	0.82	6.87	1.37
127.32	42.44	3.0	400	14.71	0.62	8.71	0.35
111.41	37.14	3.0	350	12.75	0.15	7.74	0.89

(3) Design Comments.

(a) Although Design A is simpler to build, Design B is clearly superior from a breathing resistance viewpoint. Design B was recommended and incorporated in the prototype SCBA design.

(b) The design objectives in mouthpiece pressure excursions are pressures not less than 1 cm H₂O on inhalation or more than 8 cm H₂O on exhalation at an instantaneous flow rate of 400 lpm. Design B will meet the objective pressure values at 300 lpm and comes close to meeting them at 400 lpm.

(c) Design B is considered adequate for the following reasons:

o An instantaneous flow rate of 300 lpm is appropriate to \dot{V}_e values of 95.9 (shape factor = 3.14) to 111.11 lpm (shape factor = 2.7). Those minute volumes are about as high as one can reasonably expect to see in

service.

o Even at 400 lpm, the mouthpiece pressure does not go negative on inhalation.

o Reducing the pressure drops of Design B below their present values will result in an unacceptable increase in apparatus overall size.

j. Engineering Drawings.

(1) Type. The prototype SCBA developed during Phase 2 has been documented "as built" with engineering drawings. The engineering drawings are monodetail vellum originals. For those components and assemblies where the design is not considered to be final, the drawings meet the requirements of DOD-D-1000 Level 2. For those components and assemblies considered to be final the drawings meet the requirements of DOD-D-1000 Level 3.

(2) SCBA Phase II Baseline. The Phase II drawings, which define the prototype configuration delivered for USAF testing, are listed in Table 10. The baseline drawings are given in "tree" form in Figure 22.

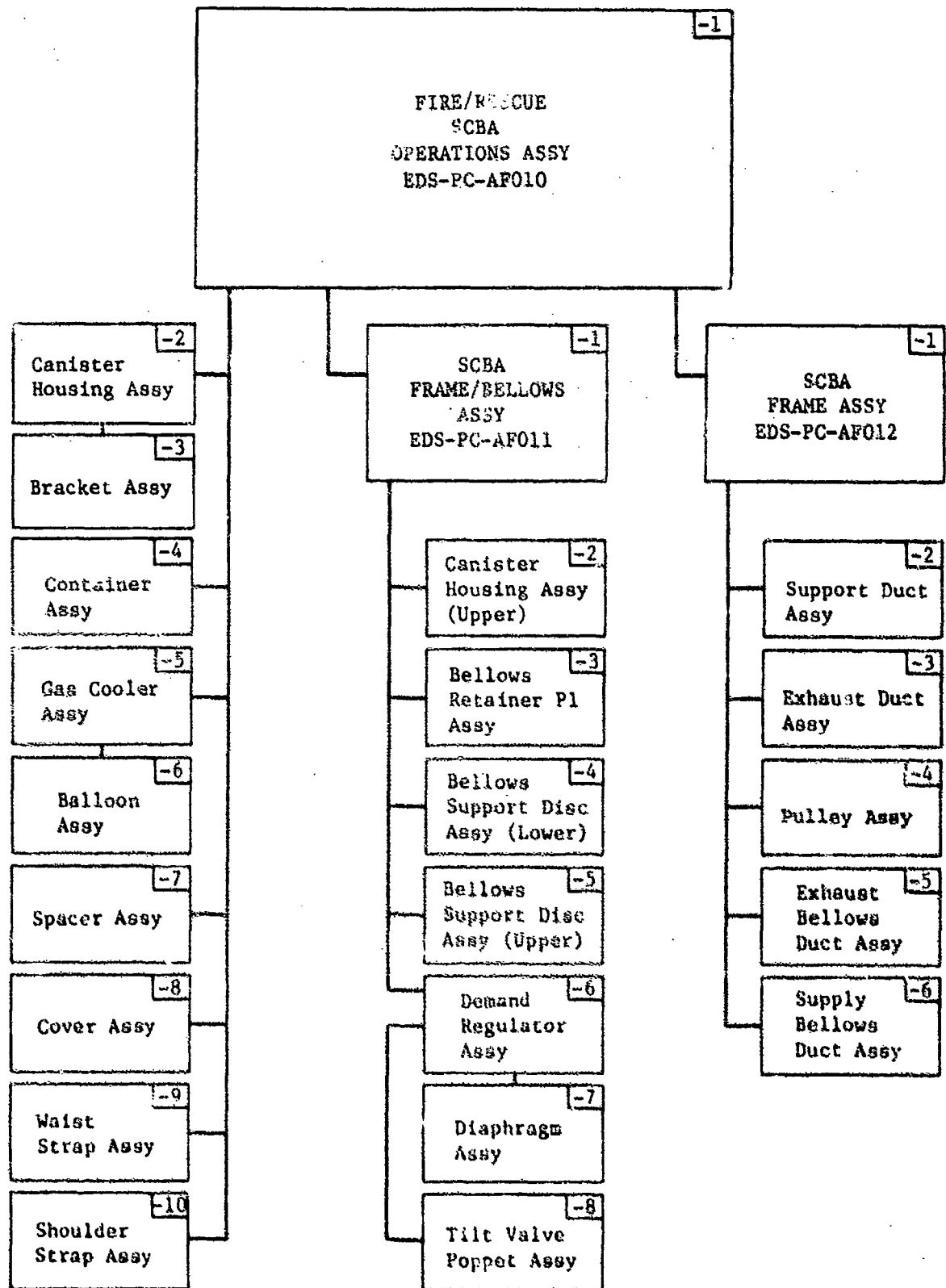


Figure 22. SCBA Drawing Tree.

TABLE 10. PROTOTYPE SCBA BASELINE CONFIGURATION.

<u>Drawing Number</u>	<u>Revision</u>	<u>Size</u>	<u>Number of Sheets</u>	<u>Title</u>
EDS-PC-AF010	N/C	F	16	SCBA Assembly, Fire/Rescue
EDS-PC-AF011	N/C	F	11	Frame/Bellows Assembly
EDS-PC-AF012	N/C	F	11	Frame Assembly

N/C - No changes.

3. BASIC OPERATIONAL PROCEDURE

This section provides a description of the controls and displays, recommended checkout procedure, and donning and operational procedures for any manned testing of the SCBA prototype. In addition, recommended turnaround procedures applicable to the prototype "as built" are provided for use during manned or unmanned testing. To facilitate reading, the figures referenced in this section, but which were first shown much earlier in the text, are repeated on foldout pages 123 through 129.

a. Controls and Displays.

The controls and displays are illustrated in Figure 8. Technical descriptions are given in section 2.b.(1).

(1) Cylinder Valve (Figure 8, item 7). It acts as a shutoff valve for the gas supply cylinder. When the SCBA is not in use, the valve is shut. It must be open when the SCBA is operating. For manned use, the cylinder valve must be opened immediately after donning the facepiece. The breathing gas supply is wasted if the valve is opened sooner.

(2) Pressure Gauge (Figure 8, item 2). The gauge indicates the pressure in psig of the breathing gas supply in the supply cylinder (item 1) only when the cylinder valve (item 7) is open.

(3) First Stage Regulator (Figure 8, item 3). The cylinder valve fits into the regulator yoke assembly. The first stage regulator reduces the pressure of the breathing gas from supply cylinder pressure to 100 psi. The regulator is factory adjusted.

(4) Low-Pressure Alarm (Figure 8, item 4). The low-pressure alarm provides an audible alarm for approximately one minute when the breathing gas supply cylinder pressure drops to approximately 500 psig.

(5) Manual Bypass Valve (Figure 8, item 5). The bypass valve is required for emergency use only and is normally closed. In the event of malfunction of the demand regulator valve and/or the supply bellows, the bypass valve is opened to bypass the demand regulator and discharge breathing gas supply from the first stage regulator into the center housing.

(6) Demand Regulator (Figure 14). The demand regulator is installed on the frame assembly, under the lower supply bellows, and vents into the supply duct connecting the two supply bellows. The demand regulator automatically provides the supply bellows with a supply of breathing gas that is proportional to the user's RMV.

b. Checkout.

Before operational testing or manned use of the SCBA, perform a pre-op checkout to assure that the following procedures have been performed.

(1) The gas supply cylinder has been charged in accordance with paragraph 3.e.(1) of Section II.

(2) The CO₂ absorbent canister has been refilled with fresh Soda-sorb® HP in accordance with Section II.3.e.(3), and installed in the canister housing in accordance with Section II.3.e.(4).

(3) The gas cooler canister has been serviced in accordance with Section II.3.e.(5) and installed in the canister housing in accordance with Section II.3.e.(6).

(4) The manual bypass valve can be manually operated and functions properly.

(5) The low-pressure alarm signal functions.

(6) The SCBA has been leak checked.

c. Donning the SCBA.

The SCBA is worn on the user's back with the inhalation and exhalation hoses leading over his right and left shoulders, respectively, to a

facepiece covering the mouth and nose. The donned position is illustrated in Figure 1. The SCBA is secured to the user's body by shoulder straps and a waist belt. It is donned by performing the following steps.

(1) Set the SCBA on the edge of a table (or equivalent), the top of which is about waist high, with the SCBA front facing the user. The gas supply cylinder should be close enough to the table edge so that the belt, illustrated in Figure 6, is hanging vertically and not touching the table.

(2) Face the SCBA and hold it in an upright position by grasping the shoulder straps near their anchor point on the frame (Figure 6).

(3) While holding the shoulder straps, turn your body slowly to the left and pass right arm under the right shoulder strap (Figure 6). Release left hand when the SCBA weight can be taken on the right shoulder.

(4) Pass left arm through left shoulder strap in a manner similar to donning a jacket.

(5) Buckle the belt.

(6) Adjust and tighten the shoulder straps so that SCBA housing bottom edges are riding on your hips.

(7) Tighten the waist belt.

(8) Reach over shoulder with either arm and grasp facepiece, lifting it up and over so that your head passes between inhalation and exhalation hoses.

(9) Place facepiece over nose and mouth, and seal.

(10) Check the facepiece for proper seal and test the check valve operation by squeezing shut the inhalation hose (right shoulder) near its connection to the facepiece and inhaling to create a vacuum. The facepiece should collapse against your face. Hold your breath for a few seconds. If the facepiece remains collapsed against the face, the mask is properly sealed and the exhalation check valve is functioning properly. Release the inhalation hose squeeze near its connection to the facepiece. Squeeze shut the exhalation hose (left shoulder) in the same manner used for the inhalation hose. Exhale to create a slight pressure in the facepiece. Hold your breath for a few seconds and, if the slight pressure remains, the inhalation check valve is functioning properly. Release the exhalation hose and breathe normally. If the facepiece does not check out properly, the SCBA must not be used.

(11) Reach back with your right hand and open the gas supply cylinder valve (Figure 8, item 7). Listen for a chirping sound from the alarm whistle.

d. Operation.

(1) Operation in a Normal Pressure Mode. Operation of the system in the normal pressure mode is as follows:

(a) The user exhales into the master bellows via the CO₂ absorbent bed and optional cooling assembly.

(b) As the master bellows expands, it causes the supply and exhaust bellows to also expand. The supply bellows fills with gas from the storage cylinder. The exhaust bellows fills with gas drawn from the user.

(c) As the user inhales, the master bellows contracts, causing the supply and exhaust bellows to contract as well. The supply bellows discharges its oxygen-rich contents into the master bellows space. The exhaust bellows discharges its contents to the outside atmosphere and to the CO₂ absorbent bed.

(2) Operation in a Positive Pressure Mode. Operation of the apparatus in a positive pressure breathing mode is similar to its operation in a normal pressure mode with the following changes:

(a) The demand regulator must be readjusted to maintain the desired degree of positive pressure at its output port.

(b) The tension on the outside exhaust valve must be increased so that it provides the desired degree of resistance to exhaust flow.

(c) The master bellows is fitted with a system designed to continuously collapse it.

e. Turnaround Procedures.

The following scheduled maintenance requirements are necessary to make the SCBA ready for operational use.

(1) Gas Cylinder Charging.

(a) Remove the cylinder from the SCBA as follows:

- o Check cylinder valve closed.
- o Loosen the gas cylinder yoke.
- o Carefully loosen the hose clamps securing the gas cylinder to the center housing.
- o Remove the gas cylinder from the straps and the rubber pad between the cylinder and housing bottom.

(b) Empty the cylinder of any remaining pressurized gas.

(c) Connect filling yoke securely to cylinder valve.

(d) Open the cylinder valve and charge the cylinder with 1800 psi of medical grade O₂.

(e) Allow gas in the cylinder to cool to approximately 68°F at 1800 psi.

(f) Close the oxygen supply valve and the cylinder valve. Vent

off O_2 remaining in charging line.

(g) Connect the high pressure N_2 supply to the charging line and open the cylinder valve.

(h) Charge the cylinder with N_2 until the cylinder pressure equals 3000 psi and the gas has cooled to approximately 68°F.

(i) Check the gas mix on an O_2 analyzer.

(2) Cylinder Installation Procedure.

(a) Place the cylinder in the two hose clamps with the solid rubber pad against the center housing bottom and the cylinder valve in the yoke attached to the first stage regulator.

(b) Tighten the cylinder yoke.

(c) Carefully tighten the hose clamps around the cylinder. They need be only snug. Excessive tightening can distort the lower housing so that it will not mate with the canister housing top or it will cause the housing to crack.

(d) Cylinder installation may be accomplished with or without the canister housing bottom attached to the canister housing top.

(3) Filling CO₂ Absorbent Canister.

The absorbent canister (Figure 10) is a flat box consisting of a bottom half into which the absorbent (Sodasorb® HP) is placed and a top half which fits over the lower half to complete the containment. Place the bottom (inner) half (Figure 10, Item 1) of the canister on a flat surface. Install the fiberglass (filter) pad (Item 2) so that it covers the wire mesh section of the bottom. Fill the bottom with 3.1 pounds of absorbent (Item 3). As the absorbent is being poured into the canister, it must be firmly and evenly tamped down. A full 3.1-pound charge, when properly tamped, will be level with the upper edge of the bottom half of the canister. It is very important that the surface of the absorbent bed be made very level and that the entire bed be carefully tamped down. This is necessary to prevent channeling of the breathing gas which will reduce the absorbing capacity of the bed, which in turn reduces the maximum safe duration of the SCBA.

When the bed is properly prepared, place the top half of the canister (Item 5) in place, making certain that its fiberglass pad (Item 4) is in place. Push the top half down evenly to close the canister. Seal the bottom edge of the top half sides to the bottom half with a 1-inch-wide strip of metal tape. The canister is now ready for installation in the SCBA canister housing.

(4) Installing CO₂ Canister in Canister Housing.

The absorbent canister (Figure 9, Item 2) fits in the top of the canister housing. Slide the canister, bottom side down, into the top

of the canister housing. A small amount of force may be necessary, since the fit is not perfect, but take care not to crack the fiberglass. When the canister is seated, it will protrude about 1/8 to 1/4 inch beyond the bottom of the top of the canister housing. Seal the space between the housing wall and the canister with a bead of silicon rubber glue in order to provide an airtight fit. This is necessary to prevent CO₂ laden air from bypassing the absorbent.

To remove the CO₂ absorbent canister, first cut all glue between the canister and the top case. Then gently work the canister out of the housing.

(5) Gas Cooler Canister.

The gas cooler canister (Figure 9, Item 4) is shipped empty. It must be filled, frozen, and sealed before operation. The procedure is:

(a) Remove the plug assembly (Figure 9, Item 5) from end of the canister and fill with 1100 ml water (approximately 3 cm from the end, with the canister standing holed end up).

(b) Keep fill hole up and place plug assembly loosely into hole. Do not press in tightly; air must be allowed to escape as the balloon is filled.

(c) Blow up the balloon until water comes out the fill hole. Then force the plug in tightly. Once the plug is in tightly, air pressure to the balloon may be released.

(d) Place unit in freezer, balloon end down.

(e) Complete freezing requires approximately 12 hours. After freezing is complete, canister is ready for use.

(f) As long as the plug assembly seal remains intact, unit may be refrozen without any special requirements. If the seal is broken, steps (a) through (c) should be repeated prior to refreezing.

(g) This procedure will be unnecessary in production models. However, it is recommended here as a precaution against ice canister fracture due to the 10-percent volume expansion which occurs when water freezes into ice. With or without the plug assembly, do not fill the canister over 90 percent full.

(6) Loading and Installing the Canister Housing Bottom.

Set the bottom spacer plate, cooler canister, and top spacer plate into the bottom as illustrated in Figure 9. Next, position the canister housing top with CO₂ canister installed in accordance with section 3.a.(4), over the bottom of the canister housing. Lower the top into the bottom until it seats on the edge stops. For the prototype housing, some manual adjustment of the housing sides may be necessary to facilitate seating of top into bottom. With top firmly seated into bottom, seal the edges with a 1- to 1 1/2-inch-wide strip of metal tape. To ensure a good seal against the apparatus's positive pressure, the taped surfaces should be completely burnished. Check closely for any tears or other possible leakage paths after the tape is applied. A tear

can be covered with a patch of metal tape. Finally, secure the two latching clamps on the sides of the canister housing and connect the plumbing fittings.

(7) Replacement of Access Port Covers.

Should the covers be removed from the access ports (Figure 4) to the supply and exhaust bellows, the covers must be replaced and sealed before operating the SCBA. The following procedure is required:

(a) Remove all sealant from cover and base plate to which it seals.

(b) Flatten cover as much as possible.

(c) Clean sealing side of cover and baseplate in area overlapped by cover and sealing tape with isopropyl alcohol.

(d) Rub sealing side of cover and baseplate in area overlapped by cover and sealing tape with fine steel wool. Protect the bellows and check valves from steel wool shavings. Vacuum all shavings from the bellows.

(e) Repeat cleaning with isopropyl alcohol.

(f) Using silicone sealant, lightly coat baseplate surface area that will be in contact with cover.

(g) Press cover in place covering hole completely.

(h) Overlay cover and surrounding area with metal tape and burnish tape completely with a bluntly rounded instrument.

(8) Access to Positive Pressure Spring.

The spring (Figure 16, Item 4) applying the tension for positive pressure operation is located under the master bellows retainer plate. The spring is attached to a cable with a bead on the end. The bead fits into a slot in a bracket which is attached to the inside of the exhaust duct on the bottom of the retainer plate.

If operation in a normal pressure mode is desired, spring tension must be released. To accomplish this, remove the retainer plate (Figure 17, Item 2) from the bellows backup plate (Figure 17, Item 5) and separate it far enough to reach the cable and bracket on the bottom of the retainer plate. Pull the cable from the bracket slot and release. Reassemble retainer plate to bellows backup plate, assuring that the gasket (Figure 17, Item 3) is in place. During reassembly, be careful not to inadvertently clamp the upper convolutions of the master bellows between the retainer backup plate (Figure 17, item 6) and the bellows backup plate. Note: do not overtorque the clamp screws. A small amount of silicone grease added to the gasket prior to reassembly will help assure a good seal.

SECTION III

UNMANNED TEST PROGRAM

1. REQUIREMENTS

Unmanned tests were conducted to determine the prototype SCBA compliance with contractual requirements prior to delivery to the Air Force for manned testing. These tests were conducted by Reimers Consultants in accordance with the Appendix D test plan and procedures. The tests and results are described below.

a. Breathing Resistance.

(1) Tests. Breathing resistance tests were conducted in accordance with the test setup and procedures of Appendix D, section 2.a., to validate the predictions (Table 9, page 70) developed during the Phase I design analysis for CO₂ absorbent canister Design B (Figure 20, absorbent above cooler). Pressure taps were installed in the SCBA as illustrated in Figure 21 to facilitate measurements of pressure drops. The taps have been left in place on the SCBA as an aid to the Air Force tests.

(2) Results.

(a) Waveform conditions were as described in section 2.a.(6) of the test plan.

(b) With the exception of the mouthpiece/facepiece one-way valves, the pressure drops in the apparatus were close to the predicted values (Table 11). Consequently, Data Sheet 2 of the test plan (Appendix D, page 186) was considered unnecessary and not completed.

(c) The resistance of the Koegel valve, originally selected for the mouthpiece valves, was found to run significantly higher (approximately double, as shown in Table 11) than reported in the published literature, especially at low flow rates. Only two of the three conical segments of the valve would open at low flow rates. When the flow rates became high enough to reliably open the third conical segment, the Koegel valve's performance became much closer to its predicted performance. This is the reason for the relatively low increase in Koegel valve pressure drop in Table 12, with increasing flow as compared to the other valves tested. A telephone inquiry to Mr. Koegel revealed that the data in the published literature was for fully developed, steady flow, e.g., all three conical segments open (Figure 23).

(d) The tests' results showed that for very high respiratory flows (e.g., peak flows over 200 lpm), the Koegel valve was the unchallenged best (Table 12). However, at low flows, some of the mushroom valves did as well or better. The SCBA, as delivered, was provided with both Koegel valves and low resistance valves made by Warren E. Collins, Inc., model 21032. One of the goals of the manned testing should be to arrive at a better determination of which style of valve is better for this application.

(e) The prototype SCBA, as delivered, will maintain positive facepiece pressures at peak inspiratory flows of up to 250 lpm (Figures 24 and

TABLE 11. ACTUAL VERSUS PREDICTED PRESSURE DROPS^a.Koegel Valve with Mouthpiece

Flow Element	Predicted Maximum ΔP		Actual Maximum ΔP		Ratio	
	inh	exh	inh	exh	inh	exh
1	0.032	0.032				
2	0.553	-	0.5-1.0	-	1 to 1.9	
3	0.023	-	NIL	-		
4	0.123	-	0.18	-	0.45	
5	0.281	-0.248		NA		
6	-0.502			NA		
7	-	0.020	-	NA		
8	-	0.553	-	0.5-1.0		1 to 1.
9	-	0.023	-	NIL		
10	-	0.238	-	0.05		0.
11	-	0.416	}	0.51	}	0.
12	-	0.077				
13	-	0.070				
14	-	0.118				
15	-	0.0003	-	NA		
16	-	0.50	-	0.55 ^b		1.
17	0.50	-	0.89 ^b		1.8	
18	0.000	-	NA	-		
19	7.008	-	- ^c	-	0.5-0.7	
20	0.000	0.427	NA	NA		

Mouthpiece
 ΔP re ATM
 Pressure

^a All values in inches H₂O

^b Data taken across 16 and 17 at same time

^c 3.6 (1.4 in. H₂O) and 4.6 (1.8 in H₂O),

BPM: 25.5
 TV: 2.5 liters
 RMV: 63.8 liters/minute
 Peak Flow: 200.3 lpm

TABLE 12. ΔP FOR SELECTED COMPONENTS.

<u>ELEMENT</u>			<u>PEAK FLOW RATES</u>		
			<u>200</u> <u>lpm</u>	<u>300</u> <u>lpm</u>	<u>350</u> <u>lpm</u>
1.	Koegel "Y" valve	inh	-0.85 ^a	-0.65 (0.95) ^b	-0.9 ^c
		exh	+0.5 (0.9) ^b	+0.5 (0.95) ^b	+0.5 (1.0) ^c
2.	W.E. Collins	inh	-0.58	-0.85	-1.0
	Model 21032 valve (in-line, no mouthpiece)	exh	+0.58	+0.85	+1.0
3.	SCBA with Koegel	inh	-1.1 (-1.3) ^b	-1.9	-2.2 (-2.3) ^b
	"Y" valve, nonpositive	exh	+0.9 (1.1) ^b	+1.3	+1.5
	pressure mode	Σ	2.0	3.2	3.7
4.	BioMarine 60 mask and	inh	-0.6	-1.2	-1.4
	valves only	exh	+0.65	1.1	+1.35
5.	BioMarine 60 mask and	inh	-0.8	-1.7	-2.1
	hoses, hoses bent	exh	+0.95	+1.8	-2.3
6.	BioMarine 60 full	inh	-0.5	-1.75	-2.5
	unit in positive	exh	+2.7	+4.8	+5.4
	pressure mode	Σ	3.2	6.6	7.9

^aThird conical segment failed to open.

^bNumber in parentheses is spike which occurs before third conical segment opens.

^c400 lpm peak flow.

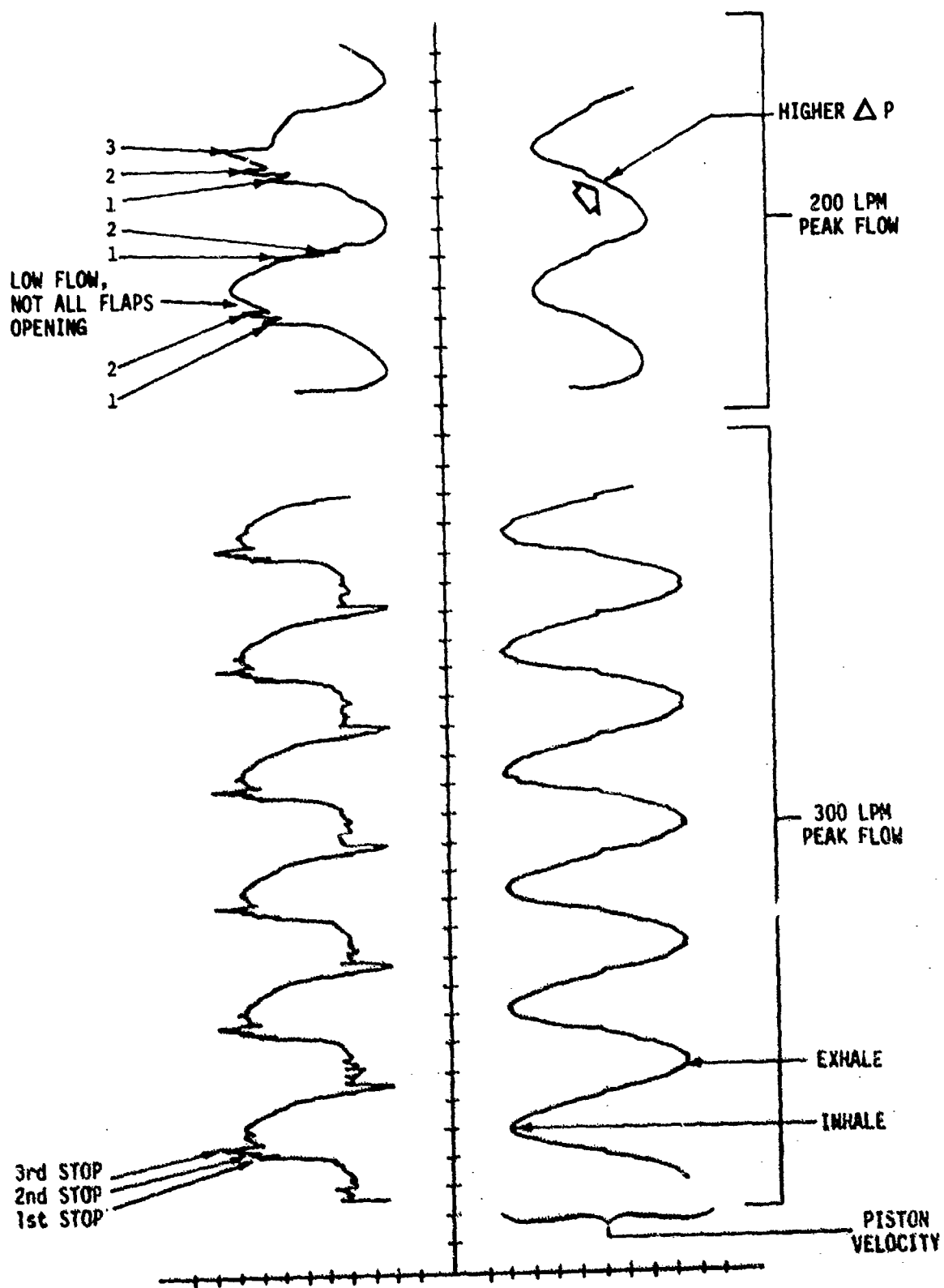
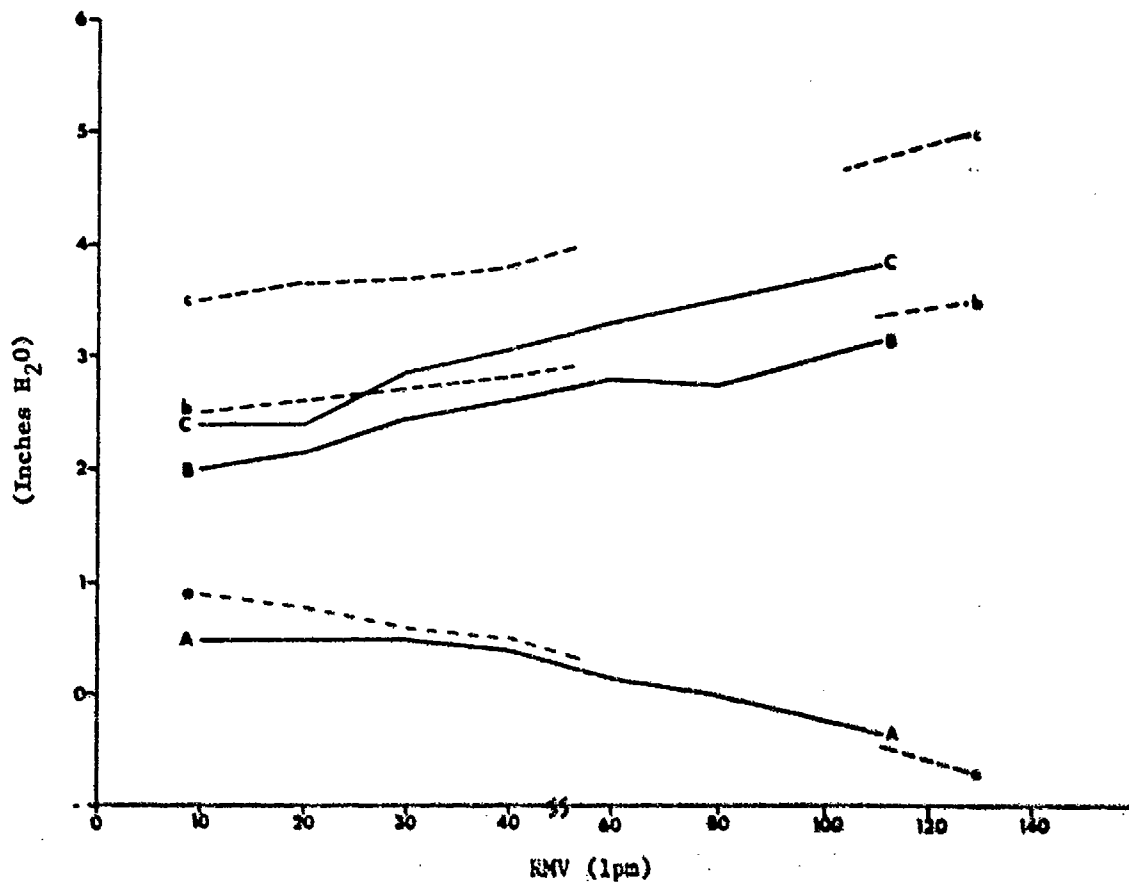


Figure 23. Koegel Valve Performance, Sine-wave Respiratory Flows.



Test No.1 Relief Valve Set at 1.4 inches H₂O ($P_1 = P_B - P_A$)

P_C = Maximum pressure

P_B = Maximum pressure without relief valve spike

P_A = Minimum pressure

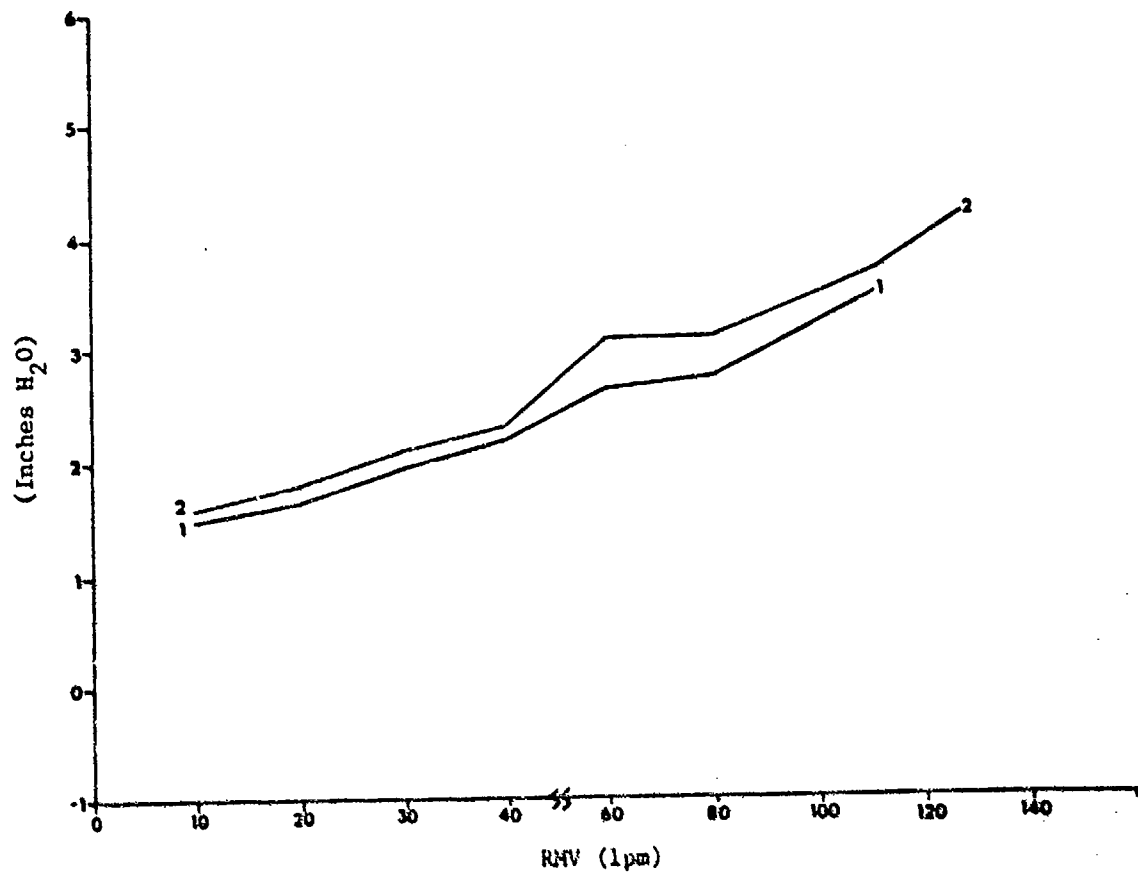
Figure 24. Mouthpiece ΔP Data for Relief Valve Set at 1.4 Inches H₂O.

25). By increasing the static bellows pressure from the present approximately 1.3 inches water to 1.8 inches water, positive inhalation facepiece pressures could be maintained at inspiratory flows up to about 350 lpm. This should be physiologically tolerable, although slightly at variance with the NIOSH limit of 1.5 inches of water.

(f) The mouthpiece pressure swing range requested by the Air Force (+8 cm water maximum on exhalation, +1 cm water minimum on inhalation, both at an instantaneous flow velocity of 400 lpm) is clearly impractical. Table 12 shows that for all instantaneous flows over 300 lpm, the amount of available pressure drop consumed by the mouthpiece one-way valves (7 cm H_2O) is 5 cm water or better. Figure 25 shows that true positive performance at high flow rates is feasible. However, it will require some relaxation of the limit on peak exhalation pressure.

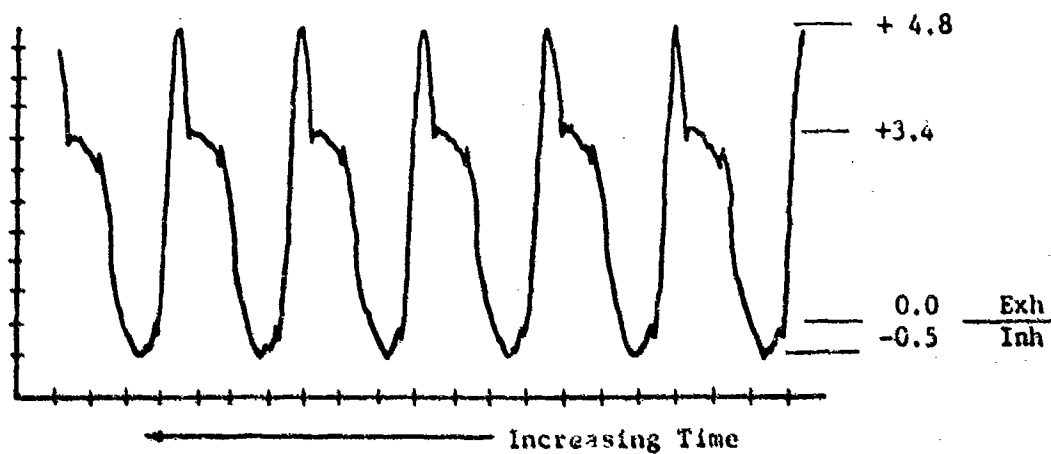
(g) The 1.4-inch H_2O relief valve setting was tried first (Figure 24). It was found to be unsuitable because the relief valve did not close reliably. Increasing the relief valve setting to 1.8 inches H_2O eliminated that problem. The unit, as delivered, has the relief valve set at 1.8 inches H_2O .

(h) The exhalation half-cycle usually exhibited two peaks (Figures 25 and 26). The first peak is the flow resistive peak. The second comes from gas being forced out directly through the relief valve at the end of exhalation cycle. It is higher, but of minor significance. The respiratory flow rate at the end of the exhalation cycle is low, whereas it is very high in the middle. Thus, the end-exhalation relief valve peaks represent a very small



Test No.2 Relief Valve Set at ~1.8 inches H₂O ($P_2 = P_b - P_a$)
 P_a, P_b, P_c analogous to P_A, P_B, P_C

Figure 25. Mouthpiece ΔP Data for Relief Valve Set at 1.8 inches H₂O.



- Notes: 1. Koegel Y Valve in mouthpiece.
2. Relief valve set at 1.8 inches H_2O .

Figure 26. Mouthpiece Respiratory Pattern

energy expenditure. Further, users will tend to vary their tidal volumes so that an end-exhalation spike is only intermittently encountered. It is possible, by adding a mechanical "dump upon full bellows" feature to the relief valve, to eliminate the relief valve peak entirely. Such a relief valve design becomes desirable in any apparatus designed to run in a mode where the bellows is always bumping against the full limit (Appendix D, section 2.c.(6)(f)). "Dump upon full bellows" valves are easily made and are employed on some currently used apparatus.

(3) Conclusions. Based on the test results obtained, the following conclusions were reached:

(a) Mouthpiece/facemask one-way valves are the dominant flow resistance in the apparatus. Unmanned test results were not sufficiently definitive for design selection.

(b) The computer model used for pressure drop predictions was reasonably accurate except for the mouthpiece/facemask one-way valves.

(c) The SCBA, as delivered, has pressure drop performance at least as efficient as existing apparatus at low flow rates and significantly better at high flow rates (Table 12).

(d) With a modest increase in main bellows static pressure, the existing SCBA design is capable of maintaining positive facemask pressures at all inspiratory flows which are likely to occur, e.g., inspiratory flows up

to about 300 lpm. The probability of occurrence of inspiratory flows above 300 lpm is so low that they do not warrant the sacrifices necessary elsewhere to achieve positive inspiratory pressures at these flow rates. The prototype will maintain a positive facemask pressure at peak flow rates up to 250 lpm (80-lpm RMV) with a static bellows pressure of approximately 1.3 inches water. With an increase in static bellows pressure of 0.5 inch water, facemask pressure would remain positive to peak flow rates of 350 lpm (111.6-lpm RMV).

b. First Stage Regulator.

(1) Tests. The performance of two candidate first stage regulators was determined for an RMV equal to 125.7 lpm in this test. The tests were conducted in accordance with the setup and procedures of Appendix D, section 2.b.

(2) Results. The test results are recorded in Tables 13 and 14, and plotted in Figure 27. Based on the data of Figure 27, it is obvious that the BioMarine first stage regulator should be selected for the SCBA gas supply design.

(3) Conclusion. The BioMarine regulator, part number 200840, should be used as the SCBA first stage regulator.

c. Supply Gas Flow Rate.

(1) Tests. These tests determined the net rate of gas flow through the SCBA under various conditions of BPN, TV, and RMV. They were conducted

TABLE 13. FIRST STAGE REGULATOR OUTLET PRESSURE FOR BIOMARINE 60 #200840

Bottle Pressure (psig)	Bottle Temp. °F	RMV ¹ (BPM)	RMV ¹ (lpm)	Breaths (Counter)	First Stage Outlet Pressure (psig)		
					Time (min)	Max.	Min. Flow (alpm)
2000	4490	72	42.4	127.5	40	113.0	112
1500	3367	70	42.4	127.5	285	107.7	106
1000	2245	67	42.4	127.5	690	102.8	99.7
900	2020	66	42.4	127.5	740	99.2	97.9
700	1571	65	42.4	127.5	881	96.1	94.8
600	1347	64	42.4	127.5	960	94.8	93.5
500	1127	63	42.4	127.5	1035	93.5	92.6
400	898	63	42.4	127.5	1114	92.1	90.8
350	786	62	42.4	127.5	1151	91.2	89.9
300	673	62	42.4	127.5	1193	90.3	89.0
250	561	62	42.4	127.5	1233	89.9	88.1
200	449	62	42.4	127.5	1270	89.0	87.2

^a Average flow = 12.7 lpm

NOTES:

1. 3.01 TV
2. Keep outlet $P_{min} \geq 70$ psig
3. Flow = $0.0917 (P_2 - P_f) / (T_1 - T_f)$

TABLE 14. FIRST STAGE REGULATOR OUTLET PRESSURE FOR SHERWOOD Selpac REGULATOR

Bottle Pressure (psig)	Bottle Pressure (fsw)	Bottle Temp. °F	RMV ¹		Breaths (Counter)	First Stage Outlet Pressure (psig)		
			(BPM)	(lpm)		Time (min)	Max.	Min. Flow (alpm)
1938	4350	80	42.4	127.5	0	0	90	88
1500	3367	74	42.4	127.5	450	10.61	87	84 7.48
1000	2245	68.5	42.4	127.5	1030	24.29	80	76 7.00
900	2020	67	42.4	127.5	1150	27.12	79	75 6.87
700	1571	66	42.4	127.5	1405	33.14	77	71 6.69
600	1347	65	42.4	127.5	1540	36.32	75	70 6.46
500	1122	64	42.4	127.5	1670	39.39	74	68 6.72
400	898	63.5	30	90.0	1790	43.39	73	68 5.13
350	786		20	60.0	1844		72	69 3.80
300	673	63	15	45.0	1900		71	69 2.78
250	561	63	15	45.0	1943		70	68 3.58
200	449	63	15	45.0	1993		69	67 3.08

NOTES:

1. 3.01 IV
2. Supply bottle gas = N₂
3. Flow Rate (average lpm) = $0.0917 \times (P_1 - P_f) / (T_1 - T_c)$

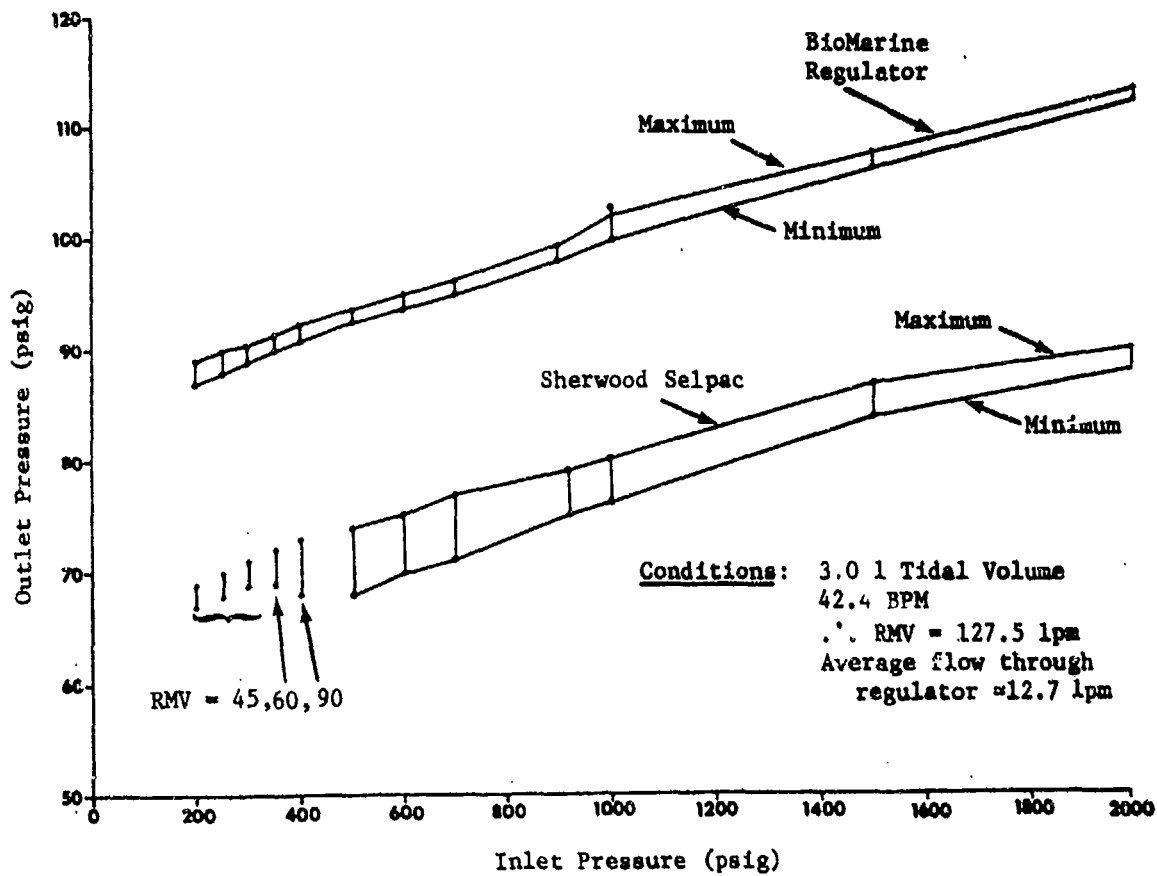


Figure 27. First Stage Regulator Outlet Pressure.

in accordance with the setup and procedures of Appendix D, section 2.c.

(2) Results.

(a) The test data are recorded in Tables 15 through 17, and are plotted graphically in Figure 28.

(b) Test runs 1 and 4 were conducted with the Sherwood Selpac regulator; test run 5 was conducted with the BioMarine regulator.

(c) The data from run 5 are considered the most appropriate data.

(d) Time constraints did not permit the tests suggested in section 2.c.(9) of Appendix D.

(e) Table 18 provides confirming data that the gas supply will last the required 120 minutes at the design RMV of 40 lpm with about a 10-minute margin.

(3) Conclusions. Based on the observations from these tests, the following conclusions were reached.

(a) The SCBA was observed to operate almost always in a push-through mode. Since the bellows sizes were selected to operate in a pull-through mode at RMVs above 40 lpm, this was a variation from expectations.

TABLE 15. SUPPLY GAS FLOW TEST, POSITIVE PRESSURE SPRING ENGAGED.

BPM	TV (l)	RMV (l/m)	Time (min:sec)	CO ₂ Removal Actual Setting	(A) Removal Rate (slpm)	Bottle Press.		Flows					Exhaust Flow Split Exh/Inh	
						Start fsw	Stop fsw	Spirometer		Bottle (4) (l/m)	Min. Safe (l/m) (2)	Level (1)		
								(1)	(1/m) (3)					
10.0	1.0	10.0	2:00	"11"	0.376	4010	3930	2.95	1.48	7.04	3.52	1.86	1.40	T
13.3	1.5	20	2:00	"19"	0.75	3830	3740	3.40	1.70	7.92	3.96	2.45	2.30	T
15.0	2.0	30	2:00	"28"	1.13	3650	3550	4.80	2.40	8.80	4.40	3.53	3.20	T
20.0	2.0	40	2:00	"31"	1.50	3350	3230	6.10	3.05	10.56	5.28	4.30	4.10	T
20.0	3.0	60	1:00	"31"	2.26	2800	2720	4.90	4.90	7.04	7.04	6.15	5.90	T
26.7	3.0	80	1:00	"31"	3.00	2520	2420	6.75	6.75	8.80	8.80	8.00	7.70	T
37.2	3.0	112.6	0:44	"31"	4.20	2060	1970	7.10	9.68	7.92	10.80	10.93	10.5	T
42.4	3.0	127.5	0:37	"31"	4.80	3310	3220	6.90	11.19	7.92	12.84	12.44	12.0	T
0.0	3.0	0.0	3:00	"31"	0.0	3000	2890	6.10	2.03	9.68	3.23	2.03	(3)	T
				(6)										

Rebreather Configuration: Bio-Marine Regulator used. Positive pressure spring engaged.

displacement (l/inch)

compliance

Main bellows

Supply bellows

Exhaust bellows

Exhaust Sample pump on

off

cm³ from +1.0 to +3.0 inch H₂O
cm³ from -2.5 to +0.5 inch H₂O
cm³ from +2.0 to +1.0 inch H₂O

Notes: 1. Note if main bellows is "bottoming out" (B) or "topping out" (T)

2. Based on exhausted pO₂ = 0.18 atm, supply gas = 60% O₂, B = 0.055, RMV = 30; B = 0.04, RMV > 30 ipm

3. Nominal value here is the steady state flow rate, F, nominally 1.0 lpm

Note: First State Outlet Pressure = psig

4. Leaky fitting in gas supply circuit

5. Relief valve setting of 1.0 inch seems leaky. Looks better at 1 3/4 inch H₂O

6. "31" = 1.25 lpm

7. Bottle H₂O Volume = 2815 ml

+ Base H₂O Volume = 210 ml

Total = 3025 ml

$$\rightarrow \dot{V}_B = 0.917 \times (P_i - P_f) = \frac{3.025 \text{ l}}{33 \text{ fsw}} (P_i - P_f)$$

TABLE 16. SUPPLY GAS FLOW TEST, BELLOWS SPRING NOT CONNECTED.

BPM	TV (%)	RMV (l/m)	Time		Bottle Press.		Flows				Design Flow	
			(min:ec)	(breaths)	Start fsw	Stc fsw	Spirometer (l) (l/m)	Bottle (l/m)		Min. Safe (l/m)	Level	
								(1)	(1/m)			
10.0	1.0	10	2:00		2860	2785	5.20	2.60	3.3	1.31	T	1.4
13.3	1.2	20	2:00		2520	2565	5.30	2.65	5.72	2.62	T	2.3
15.0	2.0	30	2:00		2480	2412	5.30	2.65	5.98	2.93	T	3.2
20.0	2.0	40	2:00		2360	2270	7.10	3.55	7.92	3.81	T	4.1
20.0	3.0	60	1:00		2210	2145	5.45	5.45	5.72	5.7	T	5.9
26.7	3.1	80	1:00		2040	1955	7.00	7.00	7.48	7.5	T	7.7
37.2	3.0	111.6	0:40		1850	1770	7.00	9.31	7.04	10.6	T	10.5
42.4	3.0	127.5	0:40		1610	1535	6.95	10.43	6.60	12.1	T	12.0
0.0	3.0	0.0	3:00		1475	1395	7.1	2.37	7.04	③	T	1.0
0.0	3.0	0.0	3:00		1370	1285	7.02	2.34	7.48	2.49	T	

Rebreather Configuration: * Note: Bellows spring not connected

displacement (l/inch) compliance

Main bellows cm^3 from +1.0 to +3.0 inch H_2O

Supply bellows cm^3 from -2.5 to +0.5 inch H_2O

Exhaust bellows cm^3 from +2.0 to +1.0 inch H_2O

Exhaust Sample pump on off

- Notes: 1. Note if main bellows is "bottoming out" (B) or "topping out" (T)
2. Based on exhaust $\text{pO}_2 = 0.16$ atm, supply gas = 60% O_2 , B = 0.055, RMV \leq 30 B = 0.05, RMV > 30 lpm
3. Nominal valve here is the steady state flow rate, F, nominally 1.0 lpm
- Note: First Stage Outlet Pressure = psig
4. Bottle (l/m) Corrected

TABLE 17. SUPPLY GAS FLOW TEST, NO SPRING/RELIEF VALVE.

BPH	TV (l)	RVV (l/m)	Time		Bottle Press.		Flows					Design Flow	
			(min:sec)	(breaths)	Start fsw	Scop fsw	Spirometer (l) (l/m)	Bottle		Min. Safe (l/m) ②	Level		
								(l)	(l/m) ④				
9.9	1.0	9.9	4:00	40	2220/65	2120/65	None	N/A	8.72	2.18	2.27	1.31	OK
13.3	1.5	20					None	N/A				2.62	
14.9	2.0	29.8	5:00	74	4080/75	3860/74	None	N/A	19.25	3.85	4.01	2.93	OK
20.0	2.0	40	5:00	100	3870/74	3630/73	None	N/A	21.0	4.2	4.37	3.81	OK
20.0	3.0	60	3:00	60	3520/72	3320/71	None	N/A	17.7	5.9	6.15	5.7	OK
26.7	3.0	80					None	N/A				7.6	
37.2	3.0	111.6	3:30	130	3170/70	2810/68	None	N/A	31.85	9.1	9.48	10.6	OK
42.4	3.0	127.5	3:00	127	2740/68	2380/66	None	N/A	31.8	10.6	11.05	12.1	OK
0.0	3.0	0.0	4:00	0	2370/66	2270/66	None	N/A	8.80	2.2	2.30	③	
									⑤				

Rebreather Configuration: No bellows spring/relief valve not installed on bellows.

displacement (l/inch) compliance - (Leaks)

Main bellows cm^3 from +1.0 to +3.0 inch H_2O

Supply bellows cm^3 from -2.5 to +0.5 inch H_2O

Exhaust bellows cm^3 from +2.0 to +1.0 inch H_2O

Exhaust Sample pump on _____ off _____

- Notes: 1. Note if main bellows is "bottoming out" (B) or "topping out" (T)
2. Based on exhaust $p\text{O}_2 = 0.18$ atm, supply gas = 60% O_2 , B = 0.055, RMV ≤ 30 B = 0.05, RMV > 30 lpm
3. Nominal value here is the steady state flow rate, F, nominally 1.0 lpm
- Note: First Stage Outlet Pressure = 90 psig + (90 psig @ 4000 fsw) + (80 psig @ 2300 fsw)
4. Bottle (l/m) Corrected
5. $V_L = 0.0917 \times (P_i - P_f) + \text{fsw}$
- $V = 1$

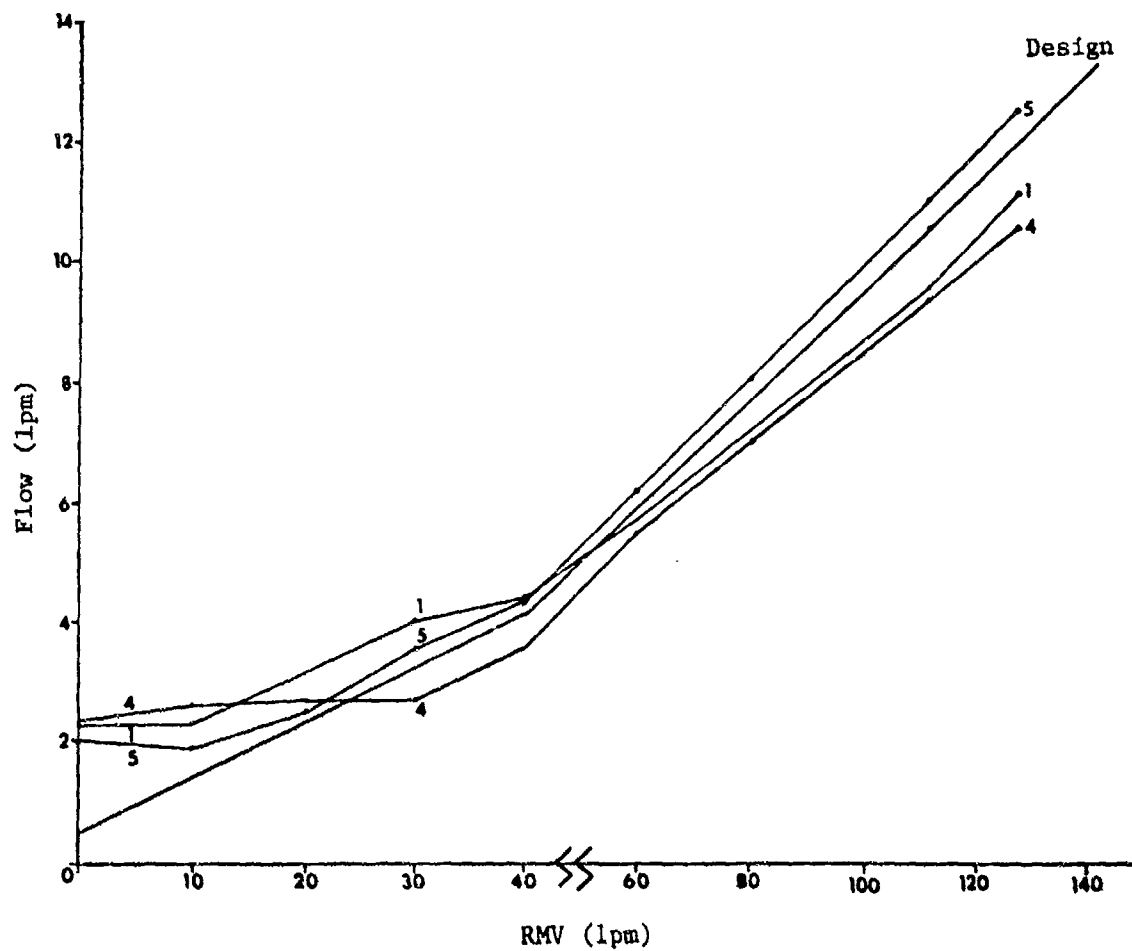


Figure 28. Supply Gas Flow Rates.

TABLE 18. CO₂ ABSORBENT TEST DATA.

TIME (min)	CO ₂ (%)		O ₂ (%)		Comments
	Exh. Box 1	Inh. Box 2	Exh. Box 1	Inh. Box 2	
1	0.4	0.0	40	45	
9	0.35				
10	3.8		48.2		+Diluent gas turned on, CO ₂ supply leak stopped
12		0.3		50.0	
17		0.4		46.5	
19			39.5		
24	~4.7		49.6		+O ₂ uptake turned off
25		0.6		55.0	
29		0.55		57.5	
30	~5.0		55.5		(32) O ₂ uptake turned on
33	~4.3		53.0		
34		0.6		54.5	
38	4.8		46.4		
40	4.8	0.6		48.5	
45	4.9		39.6		
46		0.7		43.1	
49		0.65		41.5	
51	4.9		37.0		
52		0.7		40.5	
53	4.1		36.5		
56	5.0		35.0		
57		0.75		39.4	
61		0.7		38.3	
62	5.0		33.5		
65	5.1		33.8		
66		0.8		38.6	
71		0.75		39.5	
72	5.1		35.2		
76	5.2		35.6		
77				40.0	

TABLE 18. CO₂ ABSORBENT TEST DATA (CONCLUDED).

TIME (min)	CO ₂ (%)		O ₂ (%)		Comments
	Exh. Box 1	Inh. Box 2	Exh. Box 1	Inh. Box 2	
81		0.9		40.3	
82	5.1		36.1		
85	5.2		36.3		
86		0.95		40.5	
90		0.95		41.3	
92	5.3		37.0		
98	5.5		37.0		
99		1.2		41.3	
103		1.2		41.3	
104	5.5		37.1		
110	5.7		36.8		(105.5) Supply bottle whistle
111		1.4		41.0	
116		1.5		41.1	
118	5.8		36.8		
120		1.7		41.0	
124		1.8		40.7	
125	6.1		36.5		
130	6.3		35.7		
131		2.3		37.5	Supply gas exhausted (end test)

CONDITIONS: CO₂ Canister Charge = 3.10 lb Sodasorb[®] HP
 RMV = 40.0 lpm = 2.0 l(TV) x 20.0 BPM
 Supply Gas = 60% O₂, 3000 psig charge
 CO₂ Add Rate = 1.6 slpm = 1.72 average lpm (72°F)

(b) The supply and exhaust bellows did not function well at tidal volumes of 1.0 and 1.5 liters; e.g., they did not "pump" gas as well as expected. This observation is attributed to the effects of bellows wall compliance.

(c) The Lee jet flow was approximately 2 liters per minute, which was approximately double the predicted value.

(d) The combination of higher Lee jet flow and supply bellows wall compliance resulted in a supply gas flow in acceptable range under all conditions tested. Supply gas flow at the design RMV of 40 lpm was measured at 4.3 to 4.4 lpm against a design flow of 4.0 lpm. The gas supply rate is not linear with RMV below 40 lpm. Thus, exercise profiles with alternately higher and lower RMVs, but still a 40 lpm average RMV, will result in slightly shorter gas supply duration.

(e) The wall compliance of the exhaust bellows and the attendant reduction in exhaust bellows "pumping" action are believed to be the main reasons the apparatus always runs in a push-through mode.

(f) After evaluation of the results of these tests, it was concluded that, for safety reasons, a positive pressure apparatus should always run in a push-through mode, e.g., the main bellows should always be bumping against the full limit and never against the low limit.

d. CO₂ Absorbent Canister and Gas Cooler.

(1) Tests. Tests were conducted to validate the capacity and duration of the CO₂ absorbent and gas cooler design. The tests were conducted in accordance with the test plan setup and procedures of Appendix D, section 2.d.

(2) Results.

(a) The test data are given in Tables 18 through 20.

(b) Several preliminary tests were run before useful data were obtained. The CO₂ data reported in Table 18 represent data from the best quality run available. Two previous CO₂ tests indicated similar performance; however, for various reasons, the data from these tests were considered questionable enough to warrant their unreliability.

(c) The data in Table 18 indicate that the CO₂ absorbent canister will meet the performance requirement for a duration of two hours. However, a slightly larger bed charge of Sodasorb® HP or a design change to use lithium hydroxide (LiOH) should be considered on future units, since the existing absorbent bed was obviously close to exhaustion at two hours.

(d) The cooler test data (Table 20) were obtained without CO₂ addition and, therefore, no heat generation in the CO₂ absorbent canister. The data reported in Table 19 were taken with the addition of CO₂. Tables 18 and 19 represent data from the same test.

TABLE 19. GAS COOLER TEST WITH CO₂.

Test Data				Calculations							
Elapsed Time (min)	Temperature (°F)										
	Exh Box	Inh Box	Cooler In	Cooler Out	BTU ^a in min	BTU out min	$\frac{\Delta BTU^a}{min}$	BTU ^a Removed	BTU ^b in min	$\frac{\Delta BTU^b}{min}$	BTU ^b Removed
0	108	73	55	59	8.735	2.525	6.210		8.735	6.21	
7	113	72	58	61	8.735	2.642	6.093	43.47	8.735	6.09	43.47
13	110	74	70	64	8.735	2.857	5.878	80.03	8.735	5.88	80.03
21	108	79	123	97	9.097	6.463	2.634	127.05	12.54	6.08	127.05
27	107.5	83	127	102.5	9.200	7.407	1.793	142.86	13.96	6.55	163.53
32	107	86	127	104	9.200	7.700	1.500	151.82	13.96	6.26	196.28
38	108	88	122	99	9.071	6.793	2.278	160.82	12.0	5.21	233.84
44	108	89	126	103	9.174	7.506	1.668	174.49	13.4	5.89	265.1
48	108	90	127	105	9.200	7.896	1.304	181.16	13.96	6.06	288.66
54	108	90.5	128	106	9.226	8.096	1.130	188.98	14.5	6.40	325
60	108	91	128	106	9.226	8.096	1.130	195.76	14.5	6.40	363
68	111	91.5	129	104.5	9.252	7.800	1.452	204.80	15.0	7.20	414
75	110	92	129.5	106.5	9.265	8.201	1.064		15.0	6.80	465
80	109	92	130	106.5	9.278	8.201	1.077		15.47	7.27	499
87	109	93	129	106	9.252	8.096	1.156		15.0	6.90	550
93	109	93	130	107	9.278	8.306	0.972		15.47	7.16	591
102	109	93.5	131	105	9.304	8.735	0.569		15.8	7.06	655
108	109	94.5	132	110.5	9.330	8.774	0.556		16.1	7.33	698
117	108.5	95.5	133	113	9.355	8.838	0.517		16.4	7.56	764
121	108	96	133.5	115	9.367	8.890	0.477		16.5	7.61	794
126	109	97	134	115.5	9.381	8.903	0.478		16.7	7.80	832
131	109	96	131	115	9.304	8.890	0.414	261.22	15.8	6.91	871

^a Assume saturated exhaled gas; no H₂O added from CO₂ scrubber.^b Assume saturated gas to cooler; i.e., H₂O added from CO₂ scrubber.

Dry air mass flow calculated assuming main bellows (in breathing machine) condition of 88°F saturated.

TABLE 20. GAS COOLER TEST WITHOUT CO₂.

Test Data				Calculations							
Elapsed Time (min)		Temperature (°F)		BTU ^a min	BTU min	BTU ^a min	BTU ^b min	in	BTU ^b min	BTU ^b min	BTU ^b min
Inh Box	Exh Box	Inh Box	Cooler In	Cooler Out							
1	104	80	52	52	10.022	2.728	7.294	7.19	4.315	1.587	1.739
4	103	80	60	58.5	9.769	3.234	6.535	29	4.315	1.081	6.50
6	102	82.5	63	55	9.531	2.957	6.574	42	4.315	1.358	8.66
9	102	80	64.5	55.5	9.531	2.982	6.549	62	4.315	1.333	12.74
14	102	81	66	57	9.531	3.109	6.422	95	4.315	1.206	19.40
19	102	81	68	58	9.531	3.185	6.346	153	4.315	1.130	25.43
23	102	81	69	58	9.531	3.185	6.346	183	4.315	1.130	29.95
28	102	82	70	58.5	9.531	3.234	6.297	183	4.315	1.081	35.60
31	102	81.5	70	59	9.531	3.280	6.251		4.315	1.035	41.81
37	102	82	71.5	59	9.531	3.280	6.251		4.480	1.200	49.01
43	102	81.5	72	60	9.531	3.363	6.168		4.530	1.167	55.22
48	102	82	72	60	9.531	3.363	6.168		4.530	1.167	
55	102	82	72.5	60	9.531	3.363	6.168		4.594	1.231	69.23
66	102	84	72.5	60.5	9.531	3.388	6.143		4.594	1.206	82.77
86	102	84	72	61	9.531	3.439	6.092	543	4.530	1.091	106.89
90	102	84	72	62	9.531	3.541	5.990		4.530	0.989	111.25
99	125	93	78	64	16.942	3.659	13.283	621	5.183	1.524	120.15
103	123	95	86	70	19.803	5.233	14.570	781	7.772	2.539	126.25
106	123	95	88	72	19.803	5.494	14.309		8.172	2.678	138.94
111	123	96	90	74	19.803	5.772	14.031		8.572	2.800	158.54
118	123	97	92	75	19.803	5.926	13.877		9.019	3.093	171.93
120	123	98	92.5	75	19.803	5.926	13.877		9.126	3.200	178.12
128	123	100	98	79	23.349	7.712	15.637	1026	12.331	4.619	203.72
137	124	102.5	102	85	23.974	8.946	15.028		13.632	4.686	245.29
145	123	103	104.5	90.5	23.349	10.253	13.096		14.515	4.262	282.78
150	123	103.5	106	93.5	23.349	11.003	12.346	1356	15.071	4.068	304.09
155	123	104	107	96	23.349	11.734	11.615		15.462	3.728	324.43
160	123	105.5	108.5	99	23.349	12.642	10.707	1476	16.061	3.419	343.07
170	124	107	110	103	23.974	13.973	10.001	1583	16.307	2.334	377.3

^a Assume cooling based on exhale box conditions.

^b Assume cooling based on "Cooler In" conditions; use temperature $\geq 70^{\circ}\text{F}$ for calculations.

^c Increase Exhaust temperature at 90 minutes.

NOTES: 0 - 100 min EXV = 2.5 l x 20.3 RPM = 50.75 lpm
 100 - 120 min EXV = 2.5 l x 25.0 RPM = 62.5 lpm
 120 - 170 min EXV = 2.5 l x 30.0 RPM = 75.0 lpm

(e) The actual amount of heat removed by the cooler is clearly between the two extremes reported in Tables 19 and 20. The theoretical maximum amount of heat removable by the cooler is just over 500 Btu, as shown in Tables 19 and 20. The actual heat removed is believed to have been quite close to the theoretical maximum.

(3) Conclusions. The cooler seemed to work as well or better than expected, even though the container material had to be changed to 16-gauge aluminum for fabrication reasons. The cooler continued to cool for at least two hours in all tests. The rate of energy removed by the cooler also appeared reasonably stable, although the difficulty in getting good estimates of entering enthalpy made all of the heat transfer rate measurements highly approximate.

e. Oxygen Uptake Tests.

(1) Tests. Oxygen uptake tests were performed to measure the inspired pO_2 performance as a function of B and RMV. The tests were performed in accordance with the test plan setup and procedures of Appendix D, section 2.e.

(2) Results.

(a) The test data are given in Tables 21 through 25.

(b) All conditions specified in section 2.e. of the test plan were tested.

TABLE 21. OXYGEN UPTAKE TEST NO. 3.

BPM	TV (l)	QW (l/m)	B	O ₂ (%)				O ₂ Uptake (slpm)		CO ₂ Add (slpm)	O ₂ ② ③ Add Rate (slpm)	Pred pO ₂ insp. (%)	Supply psi/time (min)	Supply Flow (alpm)
				Supply Gas	Inh Mix Box	Exh Mix Box	Wain Bulb	Design ③ ①	Actual ③					
10.0	1.0	10	0.045	60	45.1	40.6				0.45	"12"			
13.3	1.5	20	0.045	60	45.8	41.3				0.90	"26"			
15.0	2.0	30	0.045	60	44.4	39.9				1.35	"41"			
20.0	2.0	40	0.045	60	38.2	33.7				1.80	"56"			
20.0	3.0	60	0.045	60	33.1	28.6				2.70	"91"			
26.7	3.0	80	0.045	60	30.1	25.6				3.60	"150"			
20.0	3.0	60	0.040		32.2	28.2				2.40	"78"			
20.0	2.0	40	0.040		34.9	30.9				1.60	"53"			

Notes: 1. Design O₂ Uptake Rate (alpm) = B x RSV

2. O₂ add rate = average supply gas flow (slpm) from Data Sheet 4 x Supply Gas % O₂

3. slpm = alpm $\times \left(\frac{491^\circ R}{5F + 460} \right) \times \left(\frac{P_{atm}}{29.92 \text{ in Hg}} \right)$

TABLE 22. OXYGEN UPTAKE TEST NO. 4.

BPM	TV (1)	RMV (l/m)	B	O ₂ (%)				O ₂ Uptake (slpm)		CO ₂ Add (slpm)	O ₂ Add Rate (slpm)	Pred pO ₂ insp. (%)	Supply psi/time (min)	Supply Flow (alpm)
				Supply Gas	Inh Mix Box	Exh Mix Box	Main Bellows	Design (3) (1)	Actual (3)					
7.0	1.0	10	0.055	59.8	54.0	48.5				0.55	15			
13.3	1.5	20	0.055	59.8	52.4	46.9				1.10	33			
15.0	2.0	30	0.055	59.8	50.4	44.9				1.65	51			
20.0	2.0	40	0.055	59.8	42.9	37.4				2.20	70			
20.0	3.0	60	0.055	59.8	35.6	30.1				3.30	122			
15	2.0	30	0.040		42.3	38.5				1.2	36			
13.3	1.5	20	0.040		44.6	40.6				0.80	23			

Notes: 1. Design O₂ Uptake Rate (alpm) = B x RMV2. O₂ add rate = average supply gas flow (slpm) from Data Sheet 4 x Supply Gas % O₂

$$3. \text{ slpm} = \text{alpm} \times \left(\frac{491^\circ \text{R}}{^\circ \text{F} + 460} \right) \times \left(\frac{P_{\text{atm}}}{29.92 \text{ in Hg}} \right)$$

TABLE 23. OXYGEN UPTAKE TEST NO. 1.

BPM	TV (1)	BMV (l/m)	B	O ₂ (l)				O ₂ Uptake (slpm)		CO ₂ Add (slpm)	O ₂ Add (slpm)	Pred pO ₂ insp. (%)	Supply psi/time (min)	Supply Flow (slpm)
				Supply Gas	Inh Mix Box	Exh Mix Box	Main Bellows	Design (3) (1)	Actual (3)					
10.0	1.0	10	0.04	59	50-51	50-51	(5)			0.40	0.40			
13.3	1.5	20	0.04	59	48	48	(5)			0.80	0.80			
15.0	2.0	30	0.04	59	44	44				1.20	1.20			
20.0	2.0	40	0.04	59	44	44				1.60	1.60			
20.0	3.0	60	0.04	59	42	42				2.40	2.40			
26.7	3.0	80	0.04	59	36	36				3.20	3.20			
37.2	3.0	111.6	0.04	59	32.5	32.5				4.46	4.46			
42.4	3.0	127.5	0.04	59						5.10	5.10			
										(4)	(4)			

Notes: 1. Design O₂ Uptake Rate (slpm) = B x BMV2. O₂ add rate = average supply gas flow (slpm) from Data Sheet 4 x Supply Gas % O₂

$$3. \text{slpm} = \text{slpm} \times \left(\frac{491.8}{P_f \times 260} \right) \times \left(\frac{P_{\text{atm}}}{29.92 \text{ in Hg}} \right)$$

4. CO₂ not added during this test

5. Relief valve leaking on Tests 18 and 38

6. ER set low, 10.7

7. Diluent gas "air" instead of "nitrogen"

8. Exhaust valve set @ 1.3 inches H₂O

TABLE 24. OXYGEN UPTAKE TEST NO. 2.

RPM	T ₁ (1)	RNV (1/m)	B	O ₂ (%)				O ₂ Uptake (slpm)		CO ₂ Add (alpm) 20 psi Meter	O ₂ Add Rate (alpm) ②③	Pred pO ₂ insp. (%)	Supply psi/time (min)	Supply Flow (alpm)
				Supply Gas	Inh Mix Box	Exh Mix Box	Min Bellows ⑦	Design ③①	Actual ③					
10.0	1.0	10	0.035	60	54	49	0.050	0.35	0.50	0.35	"9"		2850/-20	3.5
13.3	1.5	20	0.035	60	53.2	48.6	0.046	0.70	0.92	0.70	"20"		2300/+10	3.68
15.0	2.0	30	0.035	60	51	47	0.040	1.05	1.20	1.05	"31"		2050/23	3.72
20.0	2.0	40	0.035	60	49.7	45.7	0.040	1.40	1.60	1.40	"46"		1875/32	5.58
20.0	3.0	60	0.035	60	46	43.8	0.022	2.10	1.32	2.10	"68"		1600/44	6.28
26.7	3.0	80	0.035	60	44.5	42.3	0.022	2.80	1.76	2.80	"95"		1075/60	7.30
37.2	3.0	111.6	0.035	60	42.0	39.5	0.025	3.91	2.79	3.91	"93"		770/68	8.76
42.4	3.0	127.5	0.035	60	40	37.75	0.0225	4.46	2.87	4.46	50 psi "114"		450/75	17.24
													~ 90/79 ⑨	

Notes: 1. Design O₂ Uptake Rate (alpm) = B x RNV2. O₂ add rate = average supply gas flow (slpm) from Data Sheet 4 x Supply Gas % O₂

$$3. \text{slpm} = \text{alpm} \times \left(\frac{491.8}{P_f + 460} \right) \times \left(\frac{P_{atm}}{29.92 \text{ in Hg}} \right)$$

$$4. ER = B/pO_2 \text{ insp.} = 0.035/pO_2 \text{ insp.}$$

5. Exhaust valve set @ 2 inches H₂O6. At end of test O₂ meter calibration => pO₂ exh. box > pO₂ inh. box by 0.4-0.5 percent

7. "B" valve for plotting purposes

$$8. \text{Bottle flow} = 0.1915 (P_i - P_f(\text{psi}))/T(\text{min}) = \text{alpm}$$

9. Out of gas

TABLE 25. OXYGEN UPTAKE TEST NO 5.

BPM	TV (l)	RMV (l/m)	B	O ₂ (Z)				O ₂ Uptake (slpm)		CO ₂ Add (slpm)	O ₂ (2) (3) Add Rate (slpm)	Pred pO ₂ insp. (%)	Supply psi/time (min)	Supply Flow (alpm)
				Supply Gas	Inh Mix Box	Exh Mix Box	Main Bellows	Design (3) (1)	Actual (3)					
20.0	2.0	40	0.033	60	44.0	40.7				1.98	"61"		775 psi	(4)
20.0	2.0	40	0.044	60	37.0	32.6				"61"				
20.0	2.0	40	0.050	60	32.5	27.5				"61"				
20.0	2.0	60	0.050	60	~28	23				"61"				

Notes: 1. Design O₂ Uptake Rate (alpm) = B x RMV

2. O₂ add rate = average supply gas flow (slpm) from Data Sheet 4 x Supply Gas % O₂

$$3. \text{ slpm} = \text{alpm} \times \left(\frac{491^\circ \text{R}}{e_F + 460} \right) \times \left(\frac{P_{\text{atm}}}{29.92 \text{ in Hg}} \right)$$

4. Out of supply gas

(c) The measured inspired pO_2 levels were in the safe range, i.e., greater than 21 percent, in all cases. Figure 29 carries an assessment of the reliability of the data reported in Tables 18 and 21 through 25. The reasons for the designations of some as poor data are:

- o The tests appeared to take a very long time, sometimes up to 30 minutes, to reach equilibrium. In many of the early tests, insufficient time may have been allowed for the establishment of equilibrium conditions.

- o The test data proved to be heavily dependent on analyzer accuracy. Procedures were modified for Test 5 (Table 25) and the cooler test (Table 19) to measure the pO_2 difference between the inhale and exhale mixing boxes instead of measuring the pO_2 values and then taking the difference. This resulted in greater confidence in the data from those tests.

(d) The data in Figure 29 are plotted using B as the difference between inspired and expired pO_2 levels instead of the nominal B.

(3) Conclusions. The inspired pO_2 performance appeared completely acceptable under all test conditions. During manned tests, the inspired pO_2 should stay within the range of 30 to 50 percent.

f. SCBA Prototype Weight.

(1) Tests. During the test program, the fully assembled prototype

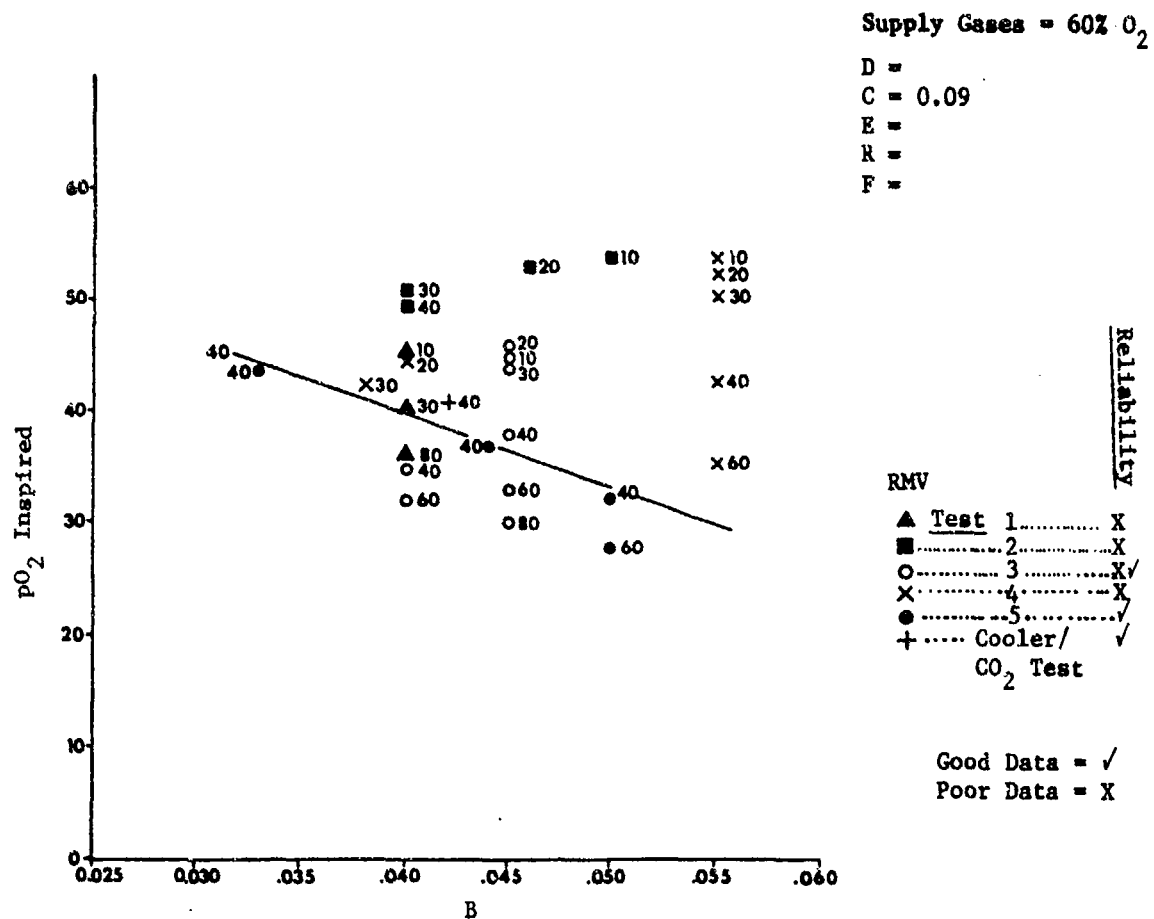


Figure 29. Oxygen Uptake Data Reliability Assessment.

weight was determined. Also, major components and/or subassemblies were weighed for comparison against predictions made during the Phase 1 design analysis.

(2) Results. The fully assembled and charged SCBA prototype weighed 34.0 pounds.

(3) Conclusions.

(a) The prototype exceeded the fully charged maximum weight design objective of 30 pounds.

(b) Based on prototype design and fabrication experience, it is believed there are several areas where weight savings can be made within reasonable costs during production engineering. These areas are:

<u>Area</u>	<u>Weight Savings (lbs)</u>
Use a fully fiber-reinforced gas cylinder.	1.9
Use lithium hydroxide instead of Sodasorb®.	1.4
Convert from water ice to CO ₂ ice as the cooling source.	1.5
Structural refinements.	<u>2.0</u>
	6.8

A production unit weight goal of 28 pounds should be considered reasonable.

g. Wearability.

(1) Tests. Wearability of the prototype was checked during the test program. The unit was donned by one of the test personnel who then moved around and ran up and down several flights of stairs.

(2) Results.

(a) The unit appears to wear well. The weight rides nicely on the wearer's hips, as intended.

(b) On future units, consideration should be given to bring the hoses around under the left arm instead of over the shoulder. This will increase head mobility and simplify the ductwork, resulting in weight and cost savings.

(3) Conclusion. The preproduction prototype design should route the inhalation/exhalation hoses under the left arm to simplify ductwork, increase head mobility, and facilitate use with CBR type protective clothing.

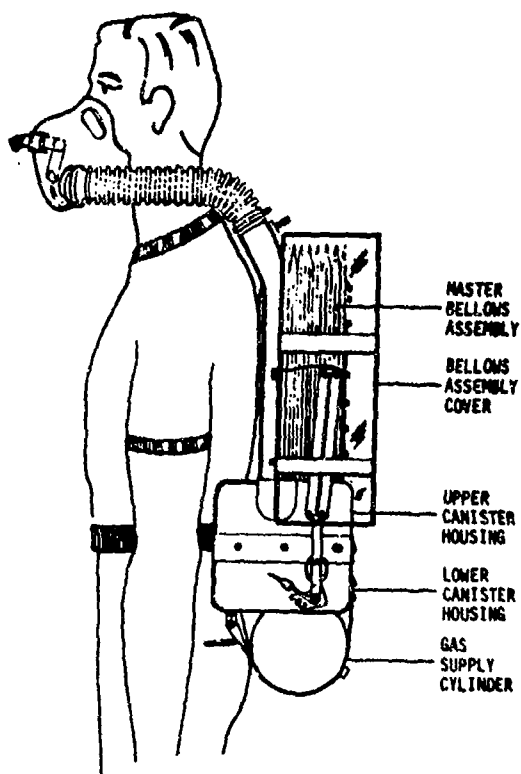


Figure 1. Left Side View.

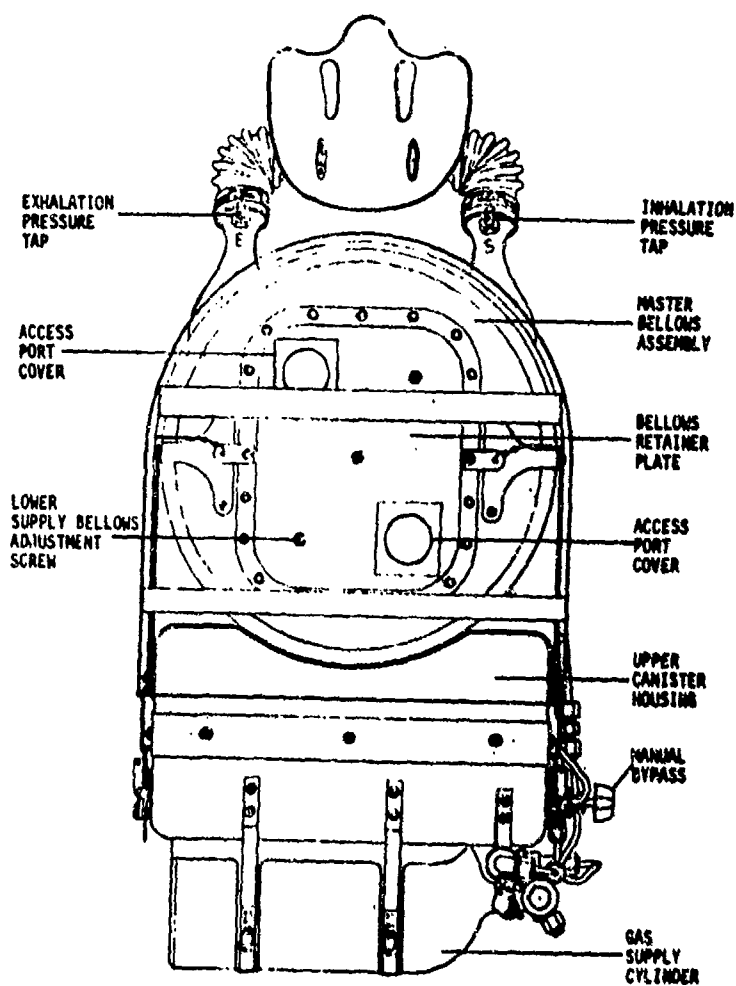


Figure 4. Rear View (Looking Forward)

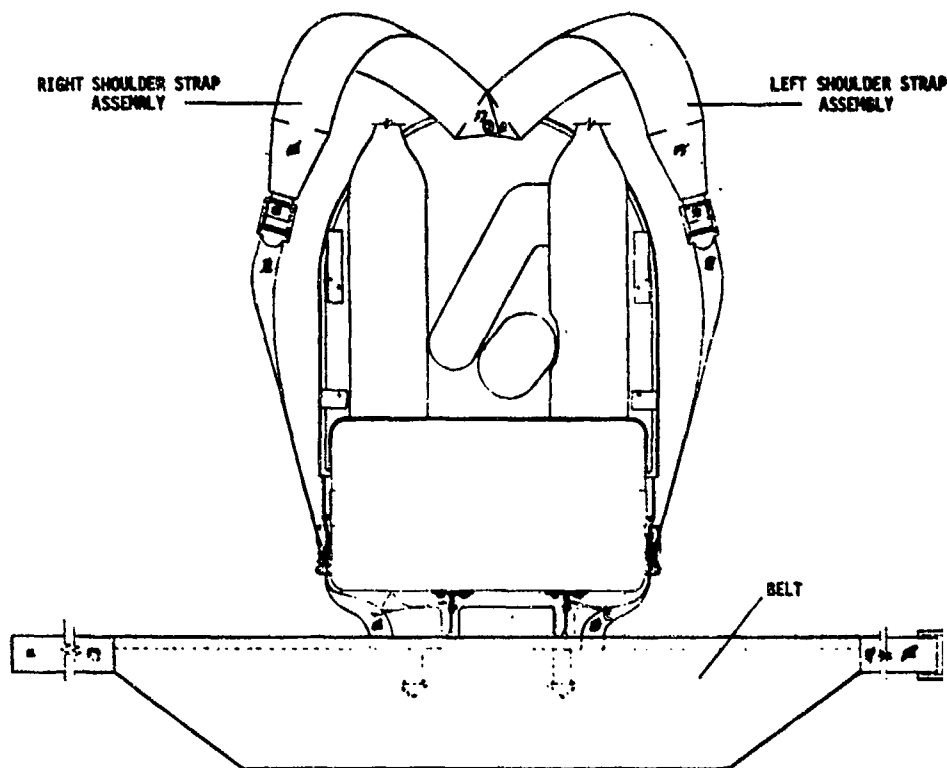


Figure 6. Harness-Front View.

1. GAS CYLINDER
2. CYLINDER PRESSURE GAUGE
3. FIRST STAGE REGULATOR
4. CYLINDER LOW-PRESSURE ALARM
5. MANUAL BY-PASS
6. HOUSING BOTTOM
7. CYLINDER VALVE
8. DEMAND REGULATOR SUPPLY LINE

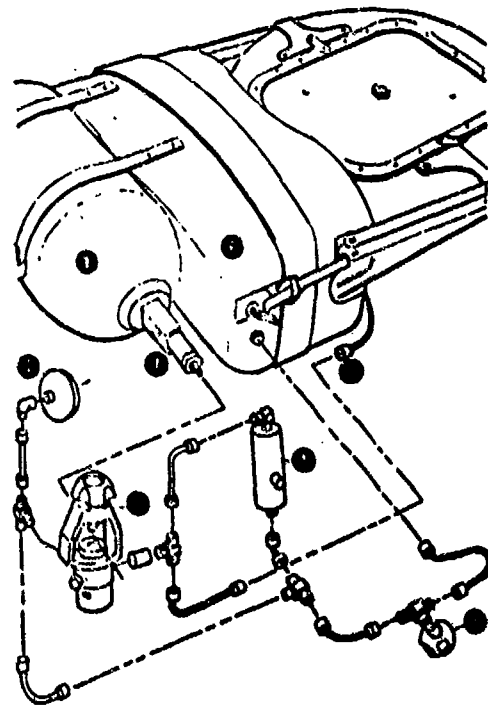


Figure 8. Gas Supply.

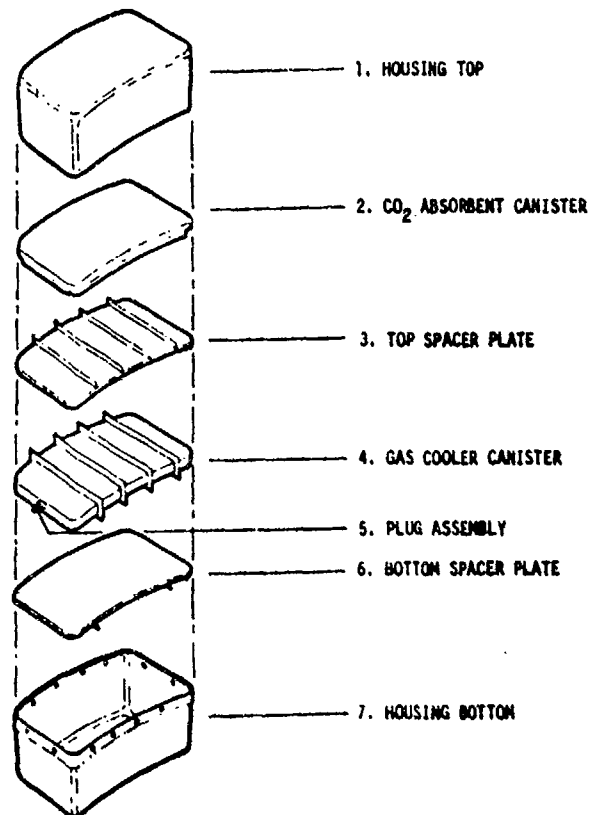


Figure 9. Canister Housing, Exploded View.

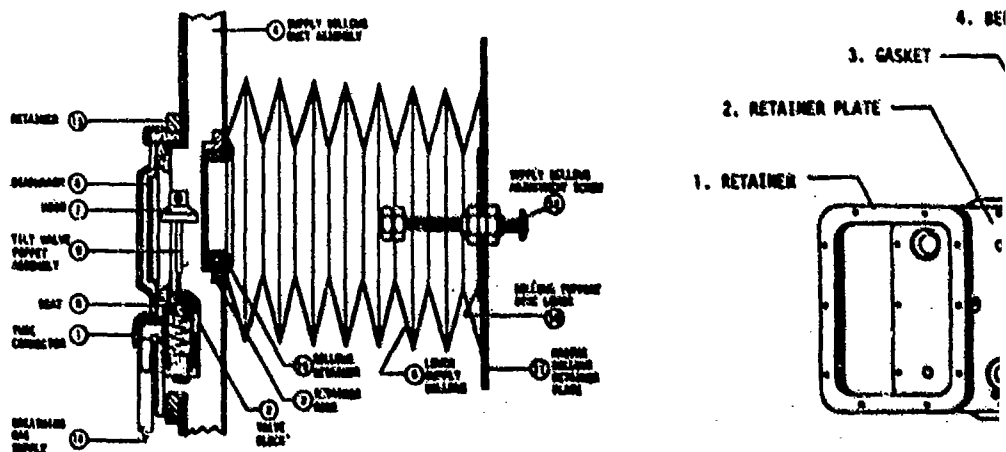


Figure 14. Demand Regulator Installation.

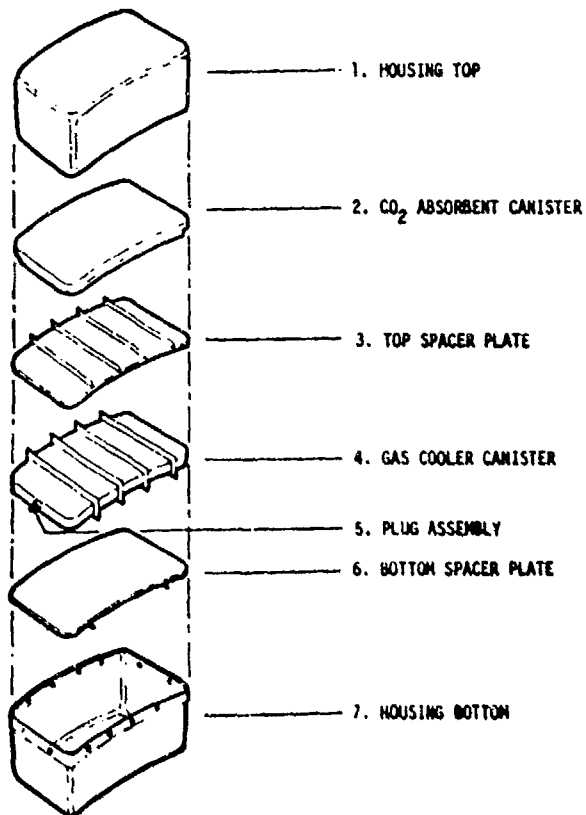


Figure 9. Canister Housing, Exploded View.

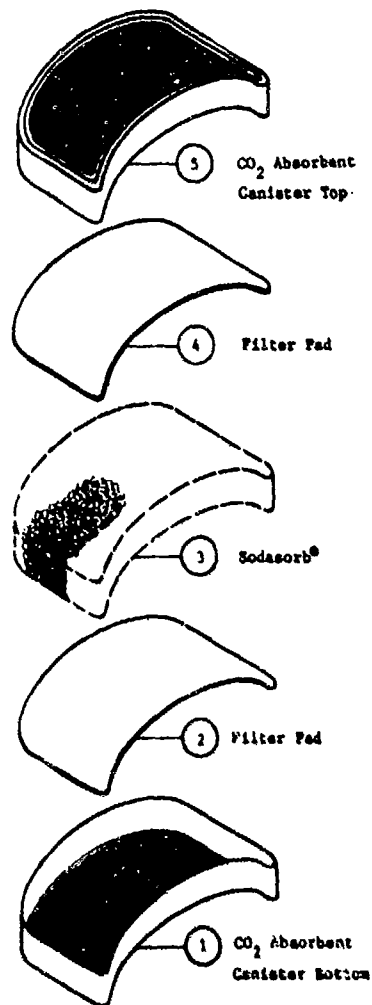
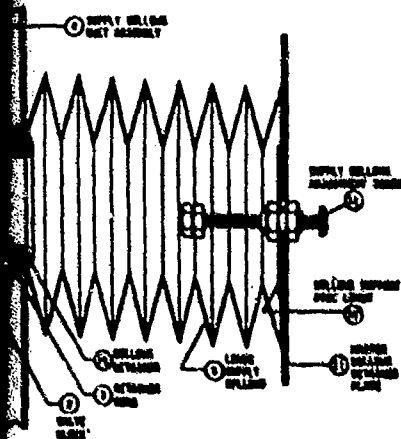


Figure 10. CO₂ Canister, Exploded View.



Demand Regulator Installation.

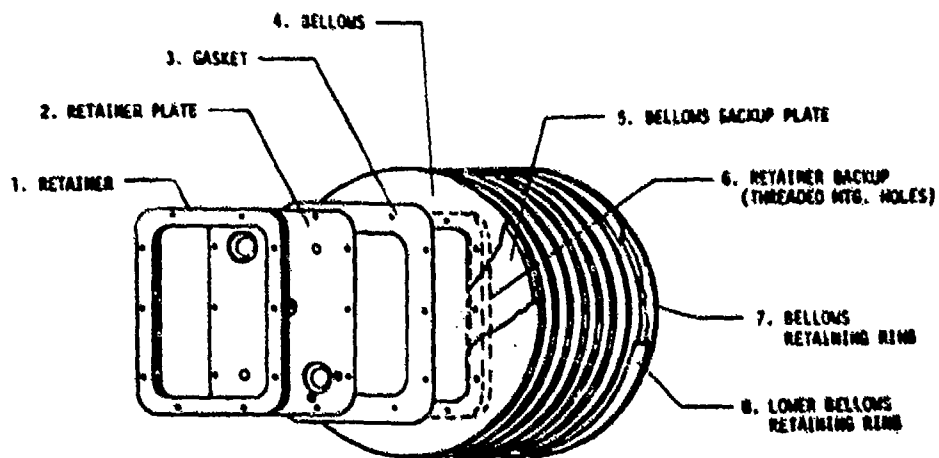


Figure 15. Master Bellows.

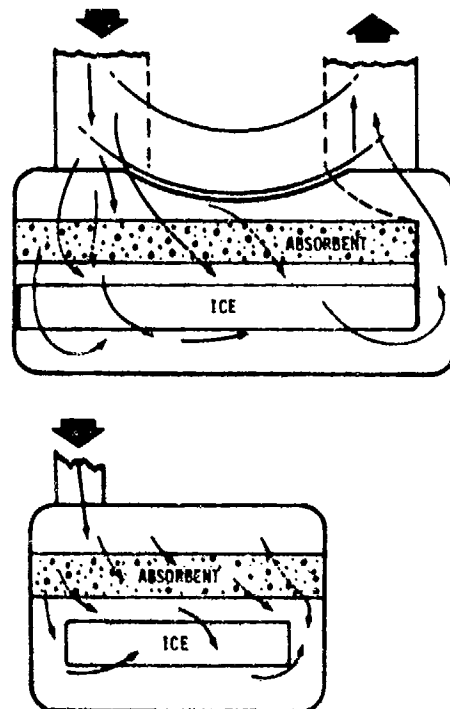


Figure 20. Design Concept "B" for Gas Scrubbing/Cooling.

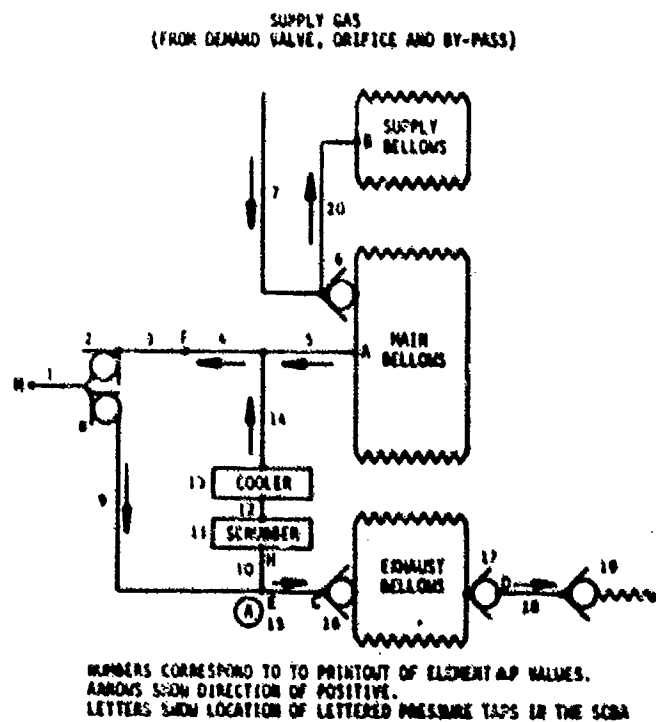


Figure 21. Flow Path Key For Air Force ΔP Program (AFDP)

APPENDIX A

DEVELOPMENT OF THE PRESSURE DROP EQUATION
FOR THE CO₂ ABSORBENT CANISTER

APPENDIX A

DEVELOPMENT OF THE PRESSURE DROP EQUATION FOR THE CO₂ ABSORBENT CANISTER.

1. FROM: "Carbon Dioxide Absorption Systems For SCUBA" and "Theory and Application of a Novel, Non-Cylindrical Low-Resistance CO₂ Absorption Canister for SCUBA," M. W. Goodman, T. W. James. USNEDU Report 4-65, U.S. Navy Experimental Diving Unit, Panama City, Florida 32407.

ITEM	L (cm)	W (cm)	H (cm)	AREA (cm ²)	FLOW (l/m)	ΔP (cm H ₂ O)
A1	15.25	5.0	36.8	184.0	81.95	3.0
A1	15.25	5.0	36.8	184.0	80.38	2.4
A1	15.25	5.0	36.8	184.0	81.33	2.2
B1	13.75	5.0	28.5	142.5	82.90	2.2
B1	13.75	5.0	28.5	142.5	81.95	2.8
C1	18.00	5.0	23.5	117.5	81.95	2.0
C1	18.00	5.0	23.5	117.5	83.52	4.1
E1	16.95	6.6	18.0	118.8	81.80	2.7
E3	16.95	6.6	18.0	118.8	80.38	3.3
E3	16.95	6.6	18.0	118.8	81.64	3.0
E4	16.85	7.5	13.7	102.8	85.97	4.1
E4	16.85	7.5	13.7	102.8	81.80	3.5
E4	16.85	7.5	13.7	102.8	82.55	3.5
E5	19.21	8.0	12.0	96.0	85.16	3.0
E5	19.21	8.0	12.0	96.0	83.18	3.5
C1	18.00	5.0	23.5	117.5	54	0.41
A1	15.25	5.0	36.8	184.0	52	1.0
C1	18.00	5.0	23.5	117.5	52	1.4
E4	16.85	7.5	13.7	102.8	52	1.2

a. Material: Baralyne

b. The initial group of data, with flows nearly the same, has been used to evaluate the effect of area. Using the flow rate factor determined elsewhere, $\Delta P \approx Q^{1.25}$, the relationship

$$\log (\Delta P / Q^{1.25}) = 0.9778 - 0.5819 \log A$$

$$\Delta P = 9.5 Q^{1.25} / A^{0.582} \quad R = -0.534$$

No statistically valid relationship between area and ΔP .

c. Comparing data on canister C1:

$$\log \Delta P = -5.093 + 2.889 \log Q$$

$$\Delta P = 0.00000807 Q^{2.89} \quad R = 0.774$$

The above relationship is possibly significant.

2. FROM: "The Design of Circle Absorbers," J. O. Elam, Anesthesiology, Vol 1, No. 1, 1958.

Flow resistance of an absorber:

$$\Delta P = 0.1 \frac{LQ}{A} \quad \text{Dimensions as before.}$$

No supporting data.

3. FROM: Letter report from MR. A. R. Allan, Jr. of Flanders Filters, Inc., to Mr. L. J. Nahn of Thomas A. Edison Industries, June 21, 1962.

ITEM	L (cm)	W (cm)	H (cm)	AREA (cm ²)	FLOW (l/m)	ΔP (cm H ₂ O)
1	57	57	2.86	3294	1130	0.305
1	57	57	2.86	3294	1695	0.508
1	57	57	2.86	3294	2260	0.762
1	57	57	2.86	3294	2825	1.016
1	57	57	2.86	3294	3390	1.270
1	57	57	2.86	3294	3955	1.626
2	27.3	27.3	2.86	746	370	0.457
2	27.3	27.3	2.86	746	565	0.660
2	27.3	27.3	2.86	746	850	1.219
2	27.3	27.3	2.86	746	1130	1.575
2	27.3	27.3	2.86	746	1415	2.134
2	27.3	27.3	2.86	746	1560	2.540

a. Material: Baralyme

b. Item 1: $\log \Delta P = -4.575 + 1.328 \log Q$

$$\Delta P = 0.0000266 Q^{1.328}$$

R = 0.9996 Totally significant.

c. Item 2: $\log \Delta P = -3.438 + 1.197 \log Q$

$$\Delta P = 0.000365 Q^{1.197}$$

R = 0.9964 Very significant.

d. Assuming $\Delta P \approx A^K$; K can be found from the above = -1.763

[Treat as temporarily valid.]

e. To obtain an overall flow correlation:

$$\log (\Delta P \cdot A^{1.763}) = 0.0637 + 1.762 \log Q$$

$$\Delta P = 1.158 \left(\frac{Q}{A} \right)^{1.762} \quad R = 0.963 \text{ Significant.}$$

The presence of $\left(\frac{Q}{A} \right)^K$, where $\frac{Q}{A}$ = velocity

is in agreement with fluid flow theory.

$$\text{If } \Delta P \approx 1, \text{ then } \Delta P = 0.405 \left(\frac{Q}{A} \right)^{1.762}$$

4. FROM: "Carbon Dioxide Management In Spacecraft Atmospheres," C. S. Coe and G. Christensen, Aerospace Medicine, February 1964, pages 110-115.

Plotted Data: (Linde)

Equation:

$$\frac{\text{inches H}_2\text{O}}{\text{foot length}} = 0.000524 \left(\frac{\text{lb air (stp)}}{\text{hour-square foot area}} \right)^{1.485}$$

$$\frac{\text{cm H}_2\text{O}}{\text{cm length}} = 0.0812 \left(\frac{\text{liters}}{\text{min-cm}^2 \text{ area}} \right)^{1.485}$$

$$\Delta P = 0.0812 L \left(\frac{Q}{A} \right)^{1.485}$$

5. FROM: Chemical Engineers Handbook, 4th Edition, pages 5-52.

For porous media:

$$\frac{\Delta P}{L} = \alpha \mu V + \beta \rho V^2$$

μ = absolute viscosity

ρ = density

α , β must be determined experimentally.

This is consistent with the correlations having exponents between 1 and 2. Exponents near 2 indicate predominantly turbulent flow, while those nearer 1 correspond to laminar flow situations.

6. OVERALL CORRELATION ATTEMPT

$\frac{\Delta P}{L}$	$\frac{\text{cm H}_2\text{O}}{\text{cm}}$	$\frac{Q}{A}$	$\frac{L}{\text{min-cm}^2}$
----------------------	---	---------------	-----------------------------

0.1066 0.3430

0.1776 0.5146

0.2664 0.6861

0.3552 0.8576

0.4441 1.0291

0.5685 1.2007

0.1598 0.4960

0.2308 0.7574

0.4262 1.1394

0.5507 1.5147

0.7462 1.8968

0.8881 2.0912

0.1661 0.4414

0.1818 0.5784

0.1770 0.6841

0.2196 0.8117

0.0715 0.3859

$$\frac{\Delta P}{L} = 0.363 \frac{Q}{A}^{1.25}$$

R = 0.964 Good.

Initial CO₂ absorbent canister design:

L = 8.26 cm

A = 198 cm²

$$\Delta P = \frac{(0.363)(8.26)}{198^{1.25}} Q^{1.25} =$$

$$0.0040 Q^{1.25}$$

Final CO₂ absorbent canister design:

L = 3.56 cm

A = 464.5 cm²

$$\Delta P = \frac{(0.363)(3.56)}{464.5^{1.25}} Q^{1.25} = 0.0006 Q^{1.25}$$

APPENDIX B

DETAILED ANALYSIS OF RESPIRATOR COOLING

APPENDIX B

DETAILED ANALYSIS OF RESPIRATOR COOLING

1. DESIGN PARAMETERS: Heat Removal = 500 Btu in 2 hours

Inlet Temperature of Fluid to be Cooled = 100°F min.

Ambient Temperature = 100°F max.

Effluent Cooling Medium Temperature = 70°F

a. Melting H₂O (Ice).

Coolant Source - Ice at 32°F

Heat Fusion = 1436 cal/mol = 143.4 Btu/lb

Specific Heat to 70°F = 38 Btu/lb

Total Heat Available = 180 Btu/lb

500 Btu requires 2.8 lb

Ice Volume = 77.5 in³

Water Volume = 79.3 in³ - allowance for expansion = 2.3%

Advantages - liquid residue, easily replenished and frozen

Disadvantages - total package 3 pounds, may tend to melt quickly

b. Other Melting Solids.

The following solids which meet the criteria of melting point

between -5 and +20°C, and boiling point more than 65°C have been considered.

<u>NAME</u>	<u>FORMULA</u>	<u>MELTING (°C)</u>	<u>BOILING (°C)</u>	<u>FUSION (Btu/lb)</u>
Antimony Chloride	SbCl_5	4	172	14.45
Selenous Oxychloride	SeOCl_2	10	168	10.96
Cyclohexane	C_6H_{12}	6.67	80	13.62
Acetic Acid	$\text{C}_2\text{H}_4\text{O}_2$	16.7	118	84.02
Dioxane	$\text{C}_4\text{H}_8\text{O}_2$	11.0	101	62.73
Formic Acid	CH_2O_2	8.4	101	106.00
Glycerol	$\text{C}_3\text{H}_8\text{O}_3$	18.1	158	85.48
Benzene	C_6H_6	5.5	80	54.18
Phosphorous Oxychloride	POCl_3	1.1	105	36.50
Hydrogen Peroxide	H_2O_2	-2	158	133.41
Acrylic Acid	$\text{C}_3\text{H}_4\text{O}_2$	12.3	141	66.65
Phenylhydrazine	$\text{C}_6\text{H}_8\text{N}_2$	19.6	244	65.36
Caprylic Acid	$\text{C}_8\text{H}_{16}\text{O}_2$	16.3	238	63.72

Since none of the compounds located have either the latent heat of fusion or the convenience and safety of water, there is no justification for using them. In comparison with water, the melting, boiling, and latent heat of fusion characteristics of hydrogen peroxide are very close and those of formic acid are reasonably comparable, however neither have any characteristics that out weigh the safety, cost, and logistical considerations of using water.

c. Solid Carbon Dioxide (Dry Ice).

(Source: Perry, 4th Ed., p. 12.21)

Solid Sublimes at $-109.6^{\circ}\text{F} = -78.7^{\circ}\text{C}$

Heat of Sublimation = 322.6 Btu/lb

Specific Heat to $70^{\circ}\text{F} = 42.7 \text{ Btu/lb}$

Total Available Heat = 365.3 Btu/lb

Dry Ice required = 1.37 pounds, vaporizes to 13.8 ft^3

Advantages - very low weight required, generally available

Disadvantages - must vent residue, low temperature will dry gas
and possibly frost-up cooling passages

d. Solid Ammonia.

(Source: Ibid, p. 3.116-3.126)

Solid Sublimes at $-107.9^{\circ}\text{F} = -77.7^{\circ}\text{C}$

Heat of Fusion = 79.4 cal/gm

Heat of Vaporization = 327.7 cal/gm

Specific Heat to $70^{\circ}\text{F} = 73.2 \text{ cal/gm}$

Total Sensible Heat = 480.3 cal/gm = 864.5 Btu/lb

Only 0.58 pounds required, vaporizes to 13.6 ft^3

Advantages - minimum weight required

Disadvantages - not readily available, venting residue required,
low temperature will dry the breathing gas, frost.

e. Liquid Ammonia.

As above, provides 354.5 cal/gm = 637.9 Btu/lb

0.78 pounds required, expanding to 18.3 ft^3

Evaporation occurs at -28°F

Advantages - low weight required

Disadvantages - all those of solid NH_3 except not as much problem with dessication and frost formation.

f. Pressurized Carbon Dioxide.

(Source: Ibid p. 3.158)

From T-S Chart:

SOURCE PRESSURE		TEMP. @ 1 ata		FRACTION SOLID	ENTHALPY cal/gm	AVAILABLE cal/gm
(psig)	(ata)	(°C)	(°F)			
100	7.8	-78	-108	0	169	27
200	14.6	-78	-108	0.04	165.5	30
300	21.4	-78	-108	0.09	161	35

At 1 ata, 100°F, H = 196 cal/gm

Available Heat @ 100 psig = 48.6 Btu/lb, @ 300 psig = 63 Btu/lb

Coolant required @ 100 psig = 10.4 lb, @ 300 psig = 7.94 lb

Advantages - generally available, easily controlled

Disadvantages - residue vented, high weight, heavy container

g. Pressurized Dichloromonofluoromethane (Freon 21).

Saturated liquid at 70°F, 23 psia = 26.5 Btu/lb

Isentropic expansion to 1 ata, 47.9°F = 21 Btu/lb

Specific Heat to 70°F = 128 Btu/lb

Available Heat = 107 Btu/lb

Coolant Required = 4.7 pounds at 23 psia = 8.3 psig

This is the optimum halogenated hydrocarbon for this application

Advantages - temperature not too low, pressure not too high

Disadvantages - residue must be vented, may cause atmospheric contamination, fairly heavy with container

h. Pneumatically Powered Refrigeration. To determine if a weight reduction exists, using compressed gas as the power source was investigated. With source pressure of 2000 psig and an airmotor efficiency of 75 percent, 15 scf air with a storage volume of 190 in³ would be needed. Total supply weight including gas and container would be about 23 pounds. Including piping and valving, the airmotor would weigh about the same as an electric motor. Thus, this approach is not effective.

APPENDIX C

DELTA P COMPUTER MODELING

TABLE C-1. AIR FORCE DELTA P PROGRAM INPUT DATA LISTING.

1	0.00000	0.79300E -6	2.0000
2	0.42700	0.31720E -5	2.0000
3	0.00000	0.56500E -6	2.0000
4	0.00000	0.91080E -5	2.0000
5	0.00000	0.70140E -5	2.0000
6	0.50000	0.82000E -5	2.0000
7	0.00000	0.10970E -4	2.0000
8	0.00000	0.18718E -4	2.0000
9	0.00000	0.40000E -2	1.2500
10	0.00000	0.15050E -5	2.0000
11	0.00000	0.22950E -5	2.0000
12	0.00000	0.39100E -6	2.0000
13	0.00000	0.68590E -5	2.0000
14	0.00000	0.20410E -5	2.0000
15	7.0000	0.62500E -4	2.0000
16	0.00000	0.14880E -5	2.0000
17	2781.0		
18	10.000		
19	3.0000		
20	6.0000		
21	2.0000		
22	730.00		
23	0.90000E -1		
24	0.64000E -1		
25	63.690		
26	25.970		
27	1.0000		
28	2.0000		
29	5.5000		
30	50.000		

TABLE C-2. DESIGN A, 200 LPM.

INDIVIDUAL FLOW ELEMENT DP'S

1 11	2 12	3 13	4 14		5 15		6 16		7 17	8 18	9 19	10 20
			DP ELEMENT NUMBER									

MAX/MIN FOR EACH FLOW ELEMENT

0.0317061	0.5538244	0.0225901	0.3541603	0.2804370	0.0000000	0.0053547	0.5538244	0.0225901	0.3874237
2.7833458	0.0531524	0.0138050	0.2422407	0.0083320	0.5011852	0.5011190	0.0082785	7.0000000	0.0004257
-0.0317061	0.0000000	0.0000000	0.0000000	-0.2477149	-0.5024905	0.0000000	0.0000000	0.0000000	0.0000000
0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000

ELEMENT VALUES FOR MAX/MIN MOUTHPIECE PRESSURE= 7.9110 AT 30 AND " 1.8594 AT 13

-0.0317061	0.0000000	0.0000000	0.0000000	-0.2477149	0.0000000	0.0053547	0.5538244	0.0225901	0.3874237
2.7833458	0.0531524	0.0138050	0.2422407	0.0083320	0.5011852	0.5011190	0.0082785	7.0000000	0.0004257
0.0317061	0.0538244	0.0225901	0.3541603	0.2804370	-0.5024905	0.0000000	0.0000000	0.0000000	0.0000000
0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.5011190	0.0082785	7.0000000	0.0004257

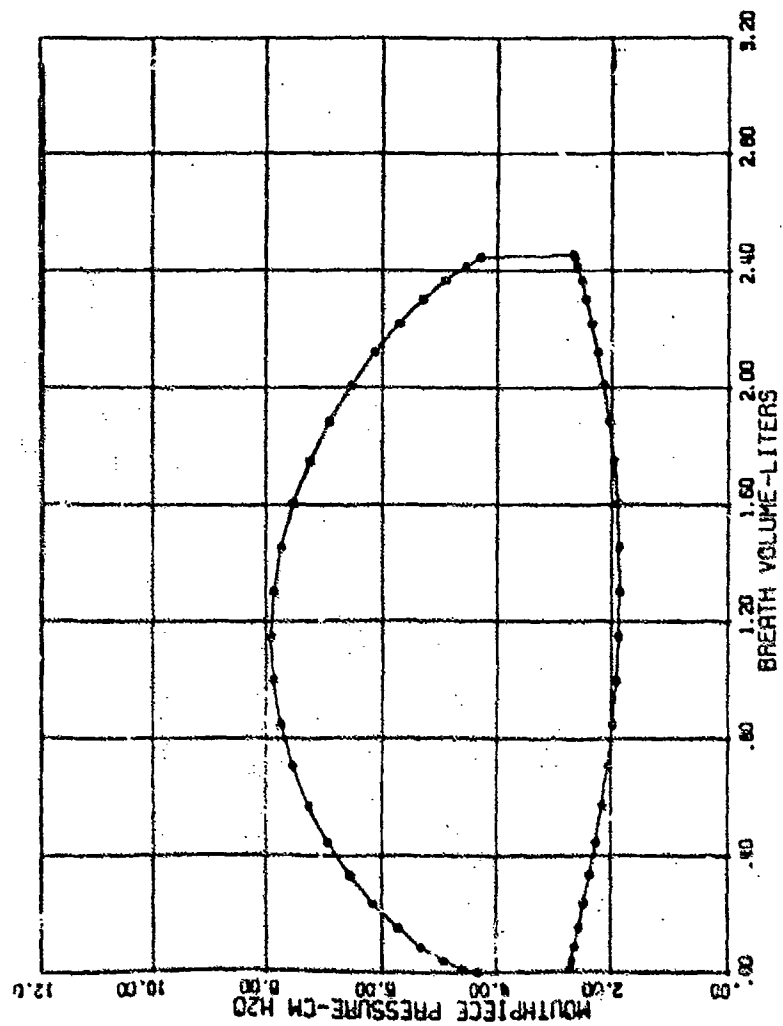


Figure C-1. Design A. 200 lpm, Breath Volume, Liters versus Mouthpiece Pressure, cm H₂O.

TABLE C-3. DESIGN A, 300 LPM.

INDIVIDUAL FLOW ELEMENT DP'S

1	2	3	4	DP ELEMENT NUMBER			6	7	8	9	10
11	12	13	14	15	16	17	18	19	20	21	22

MAX/MIN FOR EACH FLOW ELEMENT

0.0713461	0.7123848	0.0508330	0.8194465	0.6310495	0.0000000	0.0120492	0.7123848	0.0508330	0.0718009
4.6205520	0.1195955	0.0310736	0.5450891	0.0007470	0.5025893	0.5025265	0.0006208	7.0132570	0.0006578
-0.0713461	0.0000000	0.0000000	0.0000000	-0.5574173	-0.5054082	0.0000000	0.0000000	0.0000000	0.0000000
0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000032

ELEMENT VALUES FOR MAX/MIN MULTIPLE PIECE PRESSURE = 10.9716 AT 38 AND = 0.8232 AT 13

-0.0713461	0.0000000	0.0000000	0.0000000	-0.5574173	0.0000000	0.0120492	0.7123848	0.0508330	0.0718009
4.6205520	0.1195955	0.0310736	0.5450891	0.0007470	3.7025893	0.0000000	0.0000000	0.0000000	0.0006578
0.0713461	0.7123848	0.0508330	0.8194465	0.6310495	-0.5054082	0.0000000	0.0000000	0.0000000	0.0000000
0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.5025265	0.0006208	7.0132570	0.0000032

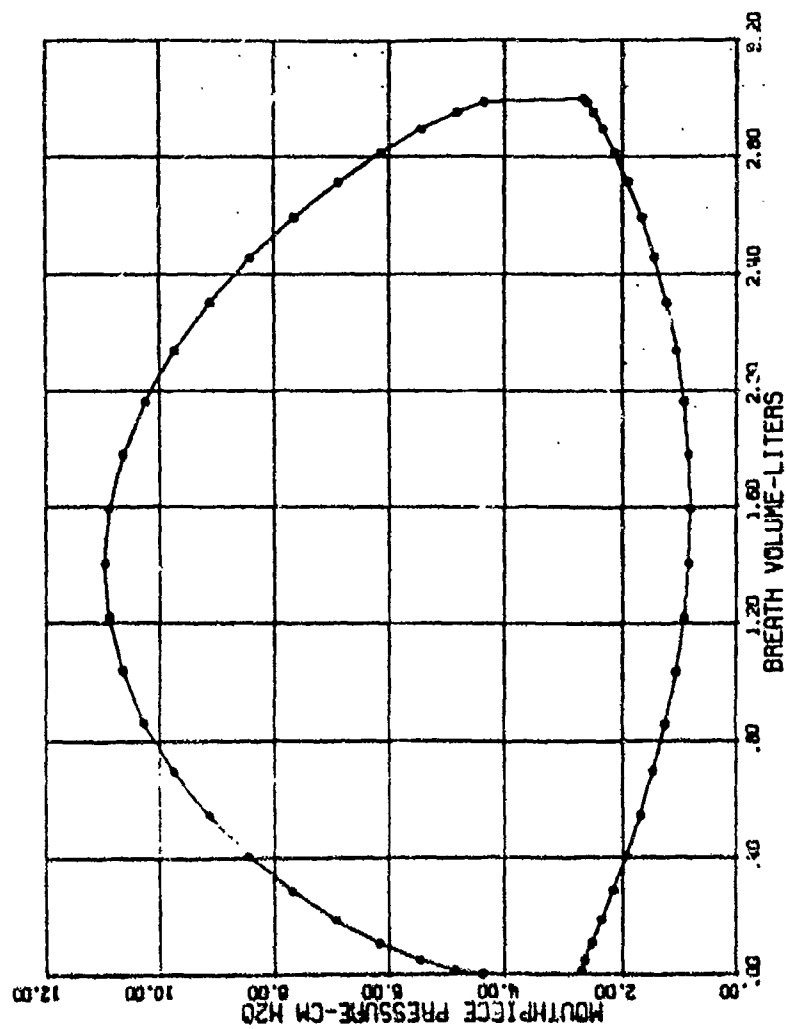


Figure C-2. Design A, 300 lpm, Breath Volume, Liters versus Mouthpiece Pressure, cm H₂O.

TABLE C-4. DESIGN A, 350 LPM.

MAX/MIN FOR EACH FLOW ELEMENT											
1		2		3		4		LP ELEMENT NUMBER		5	
11		12		13		14		6		15	
								16		17	
								8		9	
								18		19	
										10	
										20	
MAX/MIN FOR EACH FLOW ELEMENT											
0.0970171	0.8150688	0.0691232	1.1142900	0.8581066	0.0000000	0.0163846	0.0691232	0.8150688	0.0691232	1.1854920	
5.5990920	0.1626405	0.0422541	0.7412300	0.0010159	0.5036297	0.5034388	7.0252110	0.0000000	7.0252110	0.0013025	
-0.0970171	0.0000000	0.0000000	0.0000000	-0.7579803	-0.5072809	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	
0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000045	
ELEMENT VALUES FOR MAX/MIN MOUTHPIECE PRESSURE= 12.7570 AT 38 MPD = 0.1544 AT 13											
-0.0970171	0.0000000	0.0000000	0.0000000	-0.7579803	0.0000000	0.0163846	0.0691232	0.8150688	0.0691232	1.1854920	
5.5990920	0.1626405	0.0422541	0.7412300	0.0010159	0.5036297	0.0000000	0.0000000	0.0000000	0.0000000	0.0013025	
0.0970171	0.8150688	0.0691232	1.1142900	0.8581066	0.5072809	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	
0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.5034388	7.0252110	0.0000000	7.0252110	0.0012349	

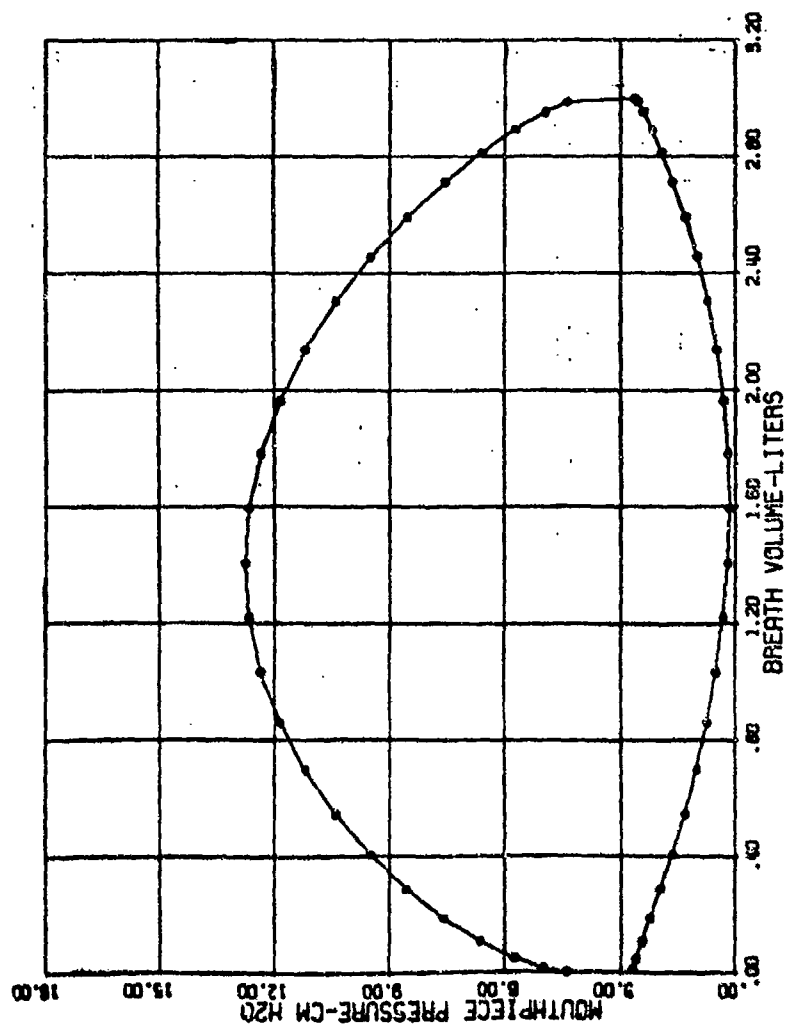


Figure C-3. Design A, 350 lpm, Breath Volume, Liters versus Mouthpiece Pressure, cm H₂O.

TABLE C-5. DESIGN A, 400 LPM.

INDIVIDUAL FLOW ELEMENT DP'S

1 11	2 12	3 13	4 14	DP ELEMENT NUMBER		7 17	8 18	9 19	10 20
				5 15	6 16				

MAX/MIN FOR EACH FLOW ELEMENT

0.1257051	0.9338202	0.0902753	1.4552710	1.1206320	0.0000000	0.0213965	0.9338202	0.0002753	1.5482520
6.6158190	0.2124056	0.0551842	0.9680516	0.0013257	0.5047404	0.5044944	0.0011187	7.0342500	0.0017011
-0.1257051	0.0000000	0.0000000	0.0000000	-0.9680516	-0.5044358	0.0000000	0.0000000	0.0000000	0.0000000
0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000

ELEMENT VALUES FOR MAX/MIN MOUTHPIECE PRESSURE= 14.7137 AT 38 AND = -6.6191 AT 13

-0.1257051	0.0000000	0.0000000	0.0000000	-0.9680516	0.0000000	0.0213965	0.9338202	0.0002753	1.5482520
6.6158190	0.2124056	0.0551842	0.9680516	0.0013257	0.5047404	0.0000000	0.0000000	0.0000000	0.0017011
0.1257051	0.9338202	0.0902753	1.4552710	1.1206320	-0.5044358	0.0000000	0.0000000	0.0000000	0.0000000
0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.5044944	0.0011187	7.0342500	0.0016128

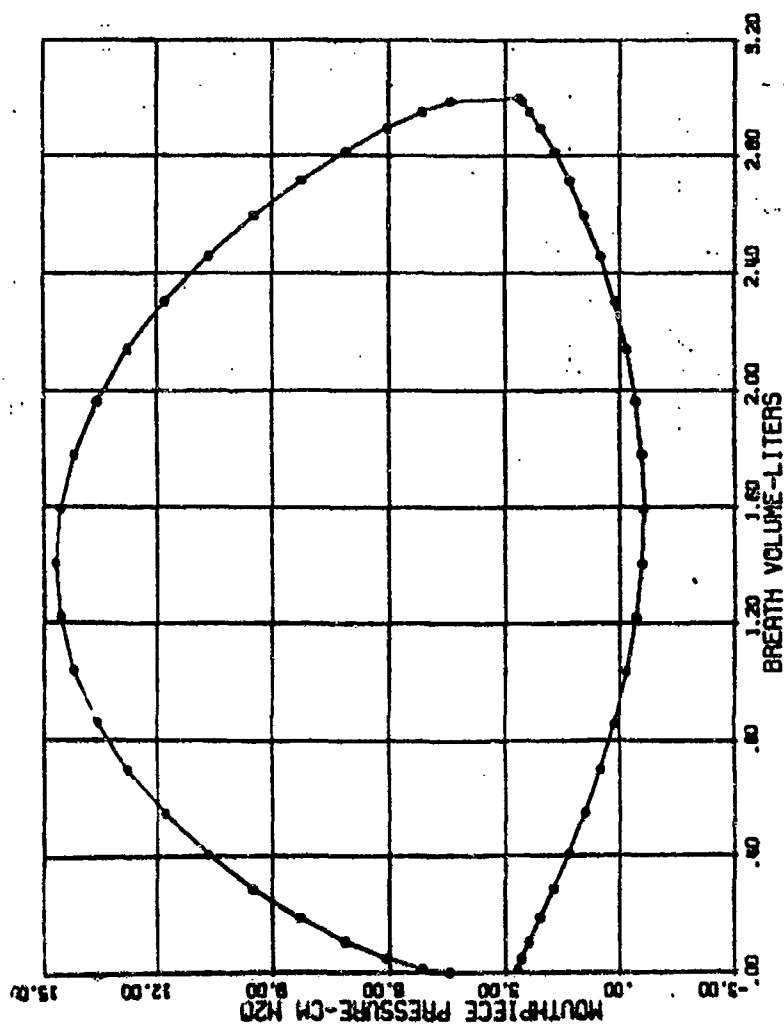


Figure C-4. Design A, 400 lpm, Breath Volume, Liters versus Mouthpiece Pressure, cm H₂O.

TABLE C-6. DESIGN B, 200 LPM.

INDIVIDUAL FLOW ELEMENT DP'S

1 11	2 12	3 13	4 14	DP ELEMENT NUMBER		7 17	8 18	9 19	10 20
				5	6				
				15	16				
0.0317061	0.5538244	0.0225901	0.1220653	0.2804370	0.0000000	0.0200506	0.5538244	0.0225901	0.2374377
0.4165128	0.0795756	0.0698574	0.1182774	0.0003320	0.5011862	0.5011190	0.0002785	7.0005230	0.0004257
-0.0317061	0.0000000	0.0000000	0.0000000	-0.2477150	-0.5024905	0.0000000	0.0000000	0.0000000	0.0000000
0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000014
ELEMENT VALUES FOR MAX/MIN MOUTHPIECE PRESSURE= 5.5077 AT 38 AND = 2.1010 AT 13									
-0.0317061	0.0000000	0.0000000	0.0000000	-0.2477150	0.0000000	0.0200506	0.5538244	0.0225901	0.2374377
0.4165128	0.0795756	0.0698574	0.1182774	0.0003320	0.5011862	0.0000000	0.0000000	0.0000000	0.0004257
0.0317061	0.5538244	0.0225901	0.1220653	0.2804370	-0.5024905	0.0000000	0.0000000	0.0000000	0.0000000
0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.5011190	0.0002785	7.0005230	0.0004916

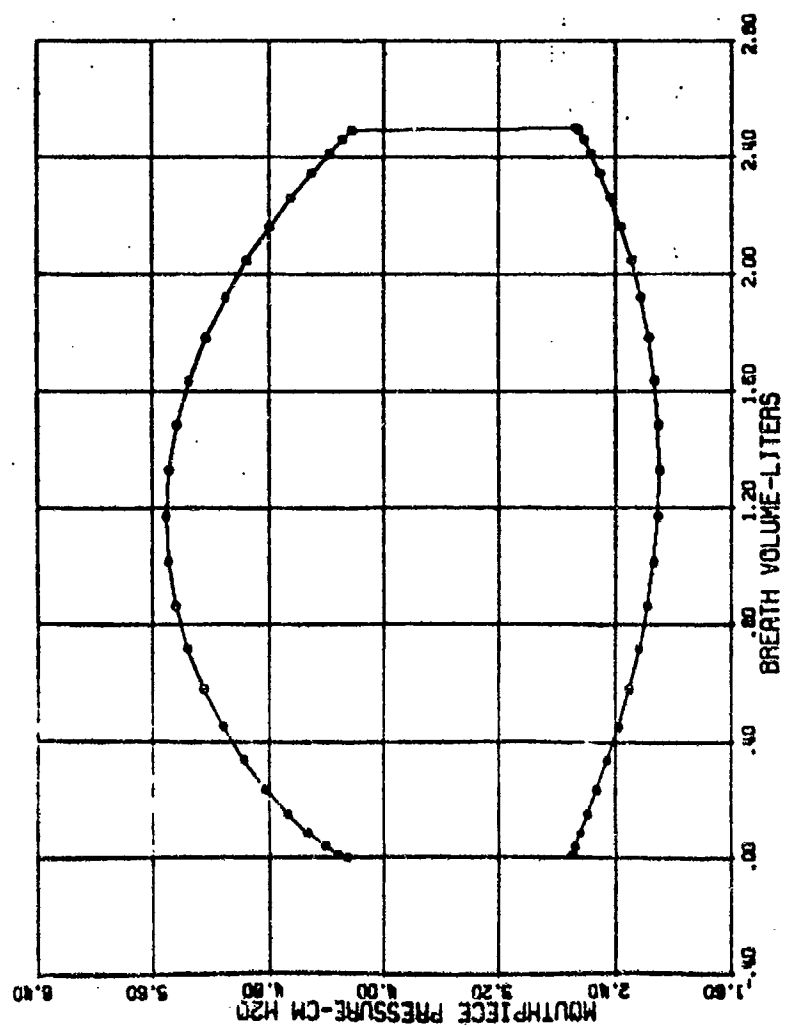


Figure C-5. Design B, 200 lpm, Breath Volume, Liters versus Mouthpiece Pressure, cm H₂O.

TABLE C-7. DESIGN B, 300 LPM.

INDIVIDUAL FLOW ELEMENT DP'S

1	2	3	4	DP ELEMENT NUMBER		7	8	9	10
				5	6				
11	12	13	14	15	16	17	18	19	20

MAX/MIN FOR EACH FLOW ELEMENT

0.0713461	0.7123848	0.0508330	0.2752181	0.6310495	0.0000000	0.0451186	0.7123848	0.0508330	0.5342989
0.6914663	0.1792891	0.1571958	0.2661521	0.0007470	0.5026693	0.5025255	0.0006288	7.0182570	0.0005578
-0.0713461	0.0000000	0.0000000	0.0000000	-0.5574173	-0.5054092	0.0000000	0.0000000	0.0000000	0.0000000
0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000032

ELEMENT VALUES FOR MAX/MIN MULTYPIECE PRESSURE= 6.8769 AT 38 AND = 1.3675 AT 13

-0.0713461	0.0000000	0.0000000	0.0000000	-0.5574173	0.0000000	0.0451186	0.7123848	0.0508330	0.5342989
0.6914663	0.1792891	0.1571958	0.2661521	0.0007470	0.5026693	0.5025255	0.0000000	0.0000000	0.0005578
0.0713461	0.7123848	0.0508330	0.2752181	0.6310495	-0.5054092	0.0000000	0.0000000	0.0000000	0.0000000
0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.5025255	0.0006288	7.0182570	0.0000066

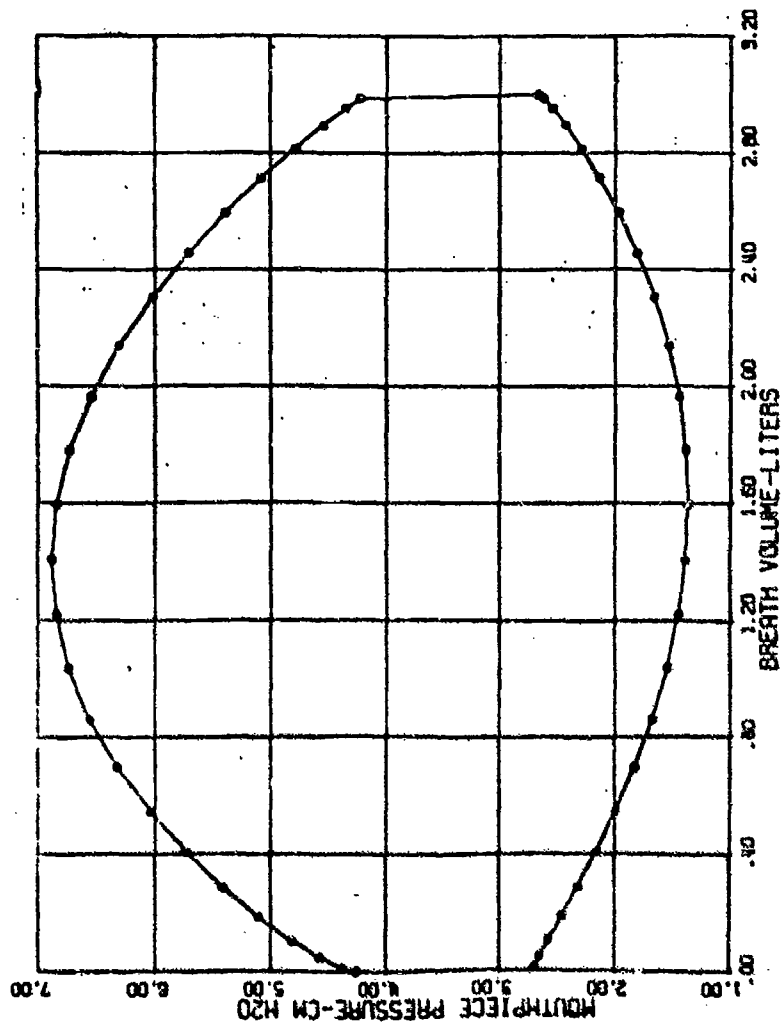


Figure C-6. Design B, 300 lpm, Breath Volume, Liters versus Mouthpiece Pressure, cm H₂O.

TABLE C-8. DESIGN B, 350 LPM.

INDIVIDUAL FLOW ELEMENT DP'S

1 11	2 12	3 13	DP ELEMENT NUMBER				7 17	8 18	9 19	10 20
			4 14	5 15	6 16					
0.0070171	0.8150658	0.0691232	0.3742441	0.8581066	0.0000000	0.0613527	0.8150688	0.0691232	0.7285329	
0.8379043	0.2437987	0.2137560	0.3619156	0.0010159	0.5035257	0.5034388	0.0000000	7.0252110	0.0013025	
-0.0070171	0.0000000	0.0000000	0.0000000	-0.7579803	-0.5072809	0.0000000	0.0000000	0.0000000	0.0000000	
0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	
ELEMENT VALUES FOR MAX/MIN MOUTHPIECE PRESSURE= 7.7356 AT 38 AND = 0.8944 AT 13										
-0.0070171	0.0000000	0.0000000	0.0000000	-0.7579803	0.0000000	0.0613527	0.8150688	0.0691232	0.7285329	
0.8379043	0.2437987	0.2137560	0.3619156	0.0010159	0.5035257	0.5034388	0.0000000	0.0000000	0.0013025	
0.0070171	0.8150658	0.0691232	0.3742441	0.8581066	-0.5072809	0.0000000	0.0000000	0.0000000	0.0000000	
0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.5034388	0.0000000	7.0252110	0.0013025	

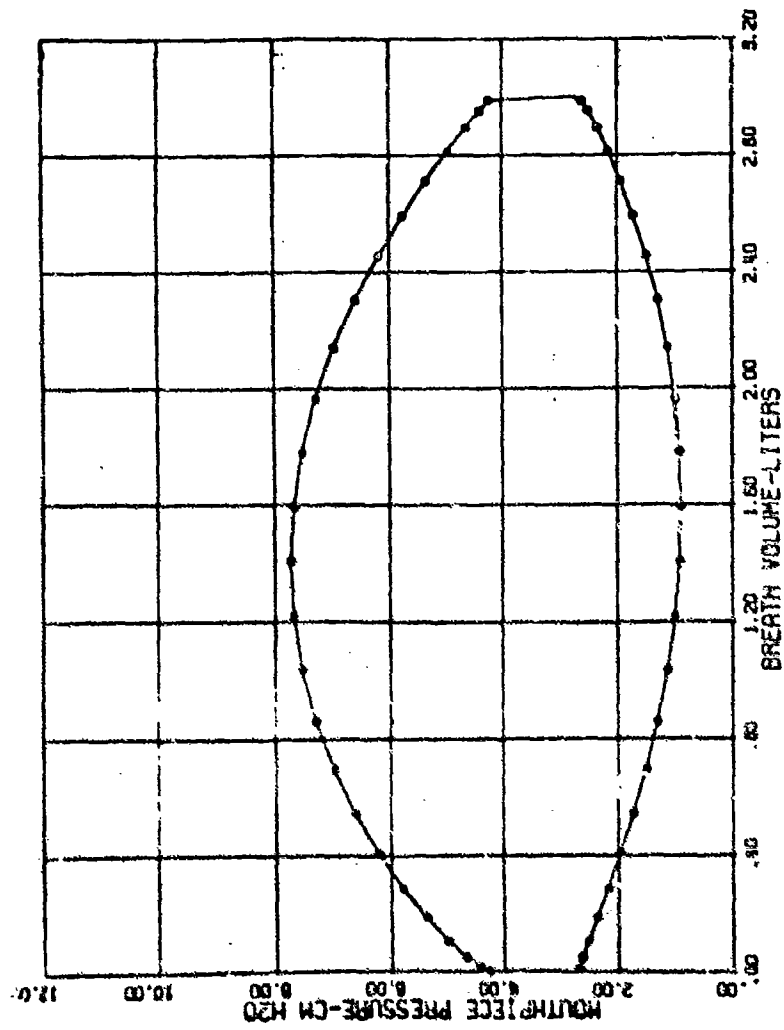


Figure C-7. Design B, 350 lpm, Breath Volume, Liters versus Mouthpiece Pressure, cm H₂O.

TABLE C-9. DESIGN B, 400 LPM.

INDIVIDUAL FLOW ELEMENT DP'S

	DP ELEMENT NUMBER									
	1	2	3	4	5	6	7	8	9	10
	11	12	13	14	15	16	17	18	19	20

MAX/MIN FOR EACH FLOW ELEMENT

0.1257051	0.9338202	0.0502753	0.4887651	1.1206920	0.0000000	0.0001270	0.5338202	0.0002753	0.9488570
0.9900573	0.3184028	0.2791669	0.4726644	0.0013257	0.5047404	0.5044944	0.0011187	7.0342550	0.0017011
-0.1257051	0.0000000	0.0000000	0.0000000	-0.5899276	-0.5094358	0.0000000	0.0000000	0.0000000	0.0000000
0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000

ELEMENT VALUES FOR MAX/MIN MOUTHPIECE PRESSURE= 8.7125 AT 38 MGD = 0.3474 AT 13

-0.1257051	0.0000000	0.0000000	0.0000000	-0.9899276	0.0000000	0.0001270	0.5338202	0.0002753	0.9488570
0.9900573	0.3184028	0.2791669	0.4726644	0.0013257	0.5047404	0.0000000	0.0000000	0.0000000	0.0017011
0.1257051	0.9338202	0.0502753	0.4887651	1.1206920	-0.5094358	0.0000000	0.0000000	0.0000000	0.0000000
0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.5044944	0.0011187	7.0342550	0.0016128

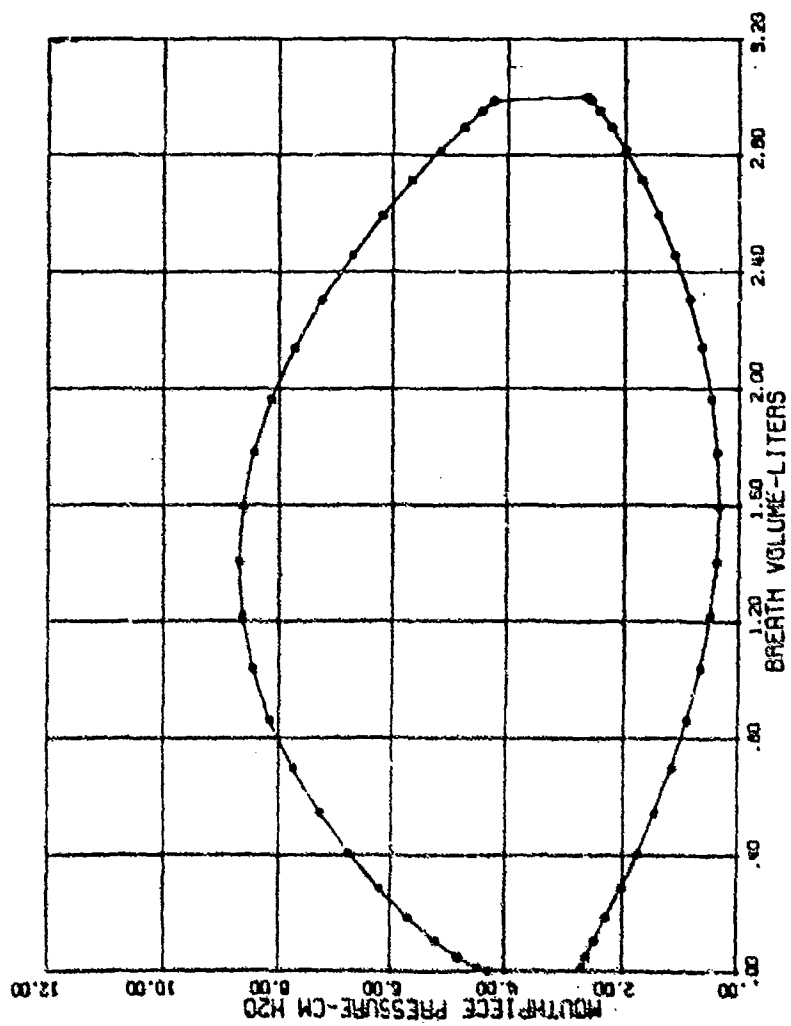


Figure C-8. Design B. 400 lpm, Breath Volume, Liters versus Mouthpiece Pressure, cm H₂O.

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APPENDIX D

TEST PLAN FOR UNMANNED TESTS CONDUCTED AT REIMERS CONSULTANTS, JULY 1981

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1. INTRODUCTION

The purpose of this test plan is to specify the tests to be performed on the prototype Self-Contained Breathing Apparatus (SCBA), hereafter referred to as the "rebreather," to determine its compliance with contractual and common sense requirements prior to delivery of the unit to the Air Force for manned testing. This test plan provides an outline for data organization so that the man-hours required for preparation of the Technical Report can be minimized.

2. TESTS TO BE PERFORMED

a. Breathing Resistance Tests.

(1) Set the rebreather up for ΔP testing (Attachment 1, Figure D-1). The rebreather mouthpiece (or facemask) should be connected to the breathing machine mouthpiece (or manikin head) with the breathing machine piston short coupled to the mouthpiece (manikin head).

(2) Using Figure 21 and Table 8 from the final report, instrument the rebreather to obtain ΔP information at as many of the listed points as possible.

(3) Fill the SCBA gas supply cylinder to 2000 psig with air. Cylinder pressure should not be allowed to drop below 500 psig during these tests.

(4) Open the cylinder valve.

(5) With the breathing machine off, measure static mouthpiece pressure. It should be approximately 1.5 inches H_2O . Readjust the negator spring tension on the main bellows if static mouthpiece pressure varies significantly from 1.5 inches H_2O .

(6) Test the SCBA under the following conditions:

BPM	TV (1)	RMV (lpm)	Peak Flow Rate (lpm)
16.0	2.0	32.0	100.5
25.5	2.5	63.8	200.3
31.9	3.0	95.7	300.7
37.2	3.0	111.6	350.6
42.4	3.0	127.5	400.6

In all cases, use a sine-wave breathing waveform with an exhalation/inhalation time ratio of 1.0.

(7) Compare the measured mouthpiece pressures with those predicted (Table 7). Also measure pressures at all points instrumented in 2.a.(2), above. Compute, using computer curve fitting procedure (coefficients D_1 , D_2 , and D_3) for as many flow elements identified in Figure 21 as possible. Compare them with those listed in Table 8.

(8) If any significant differences are encountered, attempt to determine the cause. Resolve and retest, if necessary.

(9) Record all final data on Data Sheets 1 and 2 (Attachment 2, pages 185 and 186). If the data recorded on Data Sheet 1 closely parallel the predicted data, Data Sheet 2 need not be completed. If Data Sheet 2 is completed, run the computer ΔP program using the new coefficients and compare the computer predictions with the observed results.

b. First Stage Regulator Tests.

With the setup as described in 2.a. above, run the breathing simulator at an RMV of 127.5 lpm (3.0 l TV). Monitor first stage regulator output pressure as supply cylinder pressure drops from 2000 to 200 psig.

Once the first minimum stage outlet pressure begins to fall below 70 psig, reduce the breathing rate and record the maximum RMV that can be sustained without minimum first stage outlet pressure falling below 70 psig. Note the cylinder pressure at which simulator breathing rate was first reduced. Record the data on Data Sheet 3 (Attachment 2, page 188).

c. Supply Gas Flow Rate Tests.

(1) Set the rebreather up as outlined in 2.a., above.

(2) Connect the outlet of the relief valve to the Ohio Medical Spirometer.

(3) Make sure that the rebreather and breathing simulator are free from leaks.

(4) Connect the cylinder pressure port to the 6000 fsw Heise gauge. Maximum bottle pressure for these tests should not exceed 2000 psig. Minimum bottle pressure should not be less than 500 psig.

(5) Fix the main bellows at mid-position and run a standard compliance test on the main, supply, and exhaust bellows. Record the results on Data Sheet 4 (Attachment 2, page 186).

(6) Test the rebreather under the following conditions:

BPM	TV (l)	RMV (lpm)
10.0	1.0	10
13.3	1.5	20
15.0	2.0	30
20.0	2.0	40
20.0	3.0	60
26.7	3.0	80
37.2	3.0	111.6
42.4	3.0	127.5
0.0	3.0	0.0

(7) For each test condition, compute the net rate of gas flow through the rebreather from spirometer and from cylinder pressure drops over time. Note that this requires careful time measurements in each test. Confirm the time measurement with the breath cycle counter on the breathing machine. Record the results on Data Sheet 4.

(8) Using a gas sample pump and a flowmeter, repeat the tests of 2.c.(5) above, while withdrawing gas from the rebreather at a rate equal to $B \times \text{RMV}$ with $B = 0.055$, $\text{RMV} \leq 30 \text{ lpm}$; $B = 0.04$, $\text{RMV} > 30 \text{ lpm}$. Record the results on Data Sheet 4.

(9) If time permits, repeat the tests of 2.c.(8), first with one exhaust bellows disabled, and then with one supply bellows disabled.

(10) Note: Main bellows and exhaust bellows wall compliance are not expected to be of much significance, since the ranges of wall ΔP s seen by those bellows are small and unidirectional. Supply bellows wall compliance is expected to be a significant factor. Primarily, supply bellows compliance is expected to shift the rebreather toward "pull-through" pO_2 performance. If properly balanced with the steady supply flow, supply bellows wall compliance will reduce the predicted pO_2 elevations at low RMV without any other deleterious effects.

d. CO_2 Absorbent and Gas Cooler Tests.

(1) Set up the SCBA and breathing machine approximately as shown in Figure D-2 of Attachment 1. Refer to Data Sheet 5 (Attachment 2, page 186) for required pCO_2 and temperature measurement points. Record the test setup actually used.

(2) Set the breathing machine up as follows:

BPM = 20.0 bpm

TV = 2.0 liters

RMV = 40.0 lpm

CO₂ add rate = 1.6 slpm

Expired gas = 98°F, saturated

Waveform = sine-wave with exhale/inhale

time ratio = 1.0

(3) Run this test first with the cooler installed, but not cooled. Repeat it with the cooler installed after being chilled overnight at -10°F to 0°F (standard freezer temperature range). Record the results on Data Sheet 5. "CO₂ loss rate" as indicated in Data Sheet 5 is (EXH box pCO₂ - Inh box pCO₂) RMV. It should be within ± 10 percent of the specified CO₂ add rate unless canister breakthrough is occurring, at which point it will fall below the CO₂ add rate. The "Estimated Inspired pCO₂" is the main bellows pCO₂ corrected for the dead space in the breathing apparatus mouthpiece. Use the standard dead space correction formula as given below:

Dead Space Effect

$$pCO_2, \text{ insp} = \frac{V_D}{V_{TV}} \times pCO_2, \text{ exp} + \frac{V_{TV} - V_D}{V_{TV}} \times pCO_2,$$

bag \pm tolerance.

where: $p\text{CO}_2, \text{ exp}$ = expired CO_2 level, %
 $p\text{CO}_2, \text{ insp}$ = inspired CO_2 level, %
 $p\text{CO}_2, \text{ bag}$ = breathing bag CO_2 level, %
 V_D = dead space, liters
 V_{TV} = tidal volume, liters

(4) Run the tests in section 2.d.(3) at least 3 times each or until reproducible data is obtained. If time permits, repeat them with lithium hydroxide in CO_2 absorbent canister.

(5) In each test, if possible, make an estimate of the Btu's of cooling provided by the cooler. Include the estimate in the Notes to Data Sheet 5. Attach supporting calculations to Data Sheet 5. Since the apparent cooling will be heavily dependent on dew point (or wet bulb) suppression, which will be difficult to measure in situ with available instruments, the cooling estimate will be just that, an estimate.

e. Oxygen Uptake Tests.

(1) Rig the breathing machine for oxygen uptake testing. Setup the SCBA for supply gas flow monitoring as in section 2.c., above.

(2) Test the SCBA under the following conditions:

Supply gas: (60% O₂) (40% N₂)

BPM	TV (l)	RMV (l/m)	B(\dot{V}_{O_2} / \dot{V}_E)
10.0	1.0	10	0.035, 0.04, 0.045, 0.055
13.3	1.5	20	0.035, 0.04, 0.045, 0.055
15.0	2.0	30	0.035, 0.04, 0.045, 0.055
20.0	2.0	40	0.035, 0.04, 0.045, 0.055
20.0	3.0	60	0.035, 0.04, 0.045, 0.055
26.7	3.0	80	0.035, 0.04, 0.045
37.2	3.0	111.6	0.035, 0.04
42.4	3.0	127.5	0.035, 0.04

Breathing machine exchange ratio settings are to be worked out in advance of each test as a function of inhalation box pO₂ level.

(3) The CO₂ add system should be operating during these tests and the SCBA CO₂ absorbent canister assembly should be functioning. Use of the gas cooler is desirable, but optional. CO₂ add rate is to be equal to the design oxygen uptake rate.

(4) Run each test until equilibrium is reached with respect to inspired pO₂ level and main bellows volume. Record the results on Data Sheets 4 and 6. Take care to properly identify corresponding entries in the two data sheets.

f. Weight Measurements.

Weigh the rebreather fully assembled. Also weigh major components and/or subassemblies. Note any areas where significant weight/space savings can be made with production tooling or with the redesign of existing components. Record all weights on mark-up copies of Tables 5 and 6 from the first phase report. Also note any component changes from those shown in Tables 5 and 6.

g. Wearability Tests.

Don unit, move around in it, run up and down several flights of stairs, and make an estimate of the wearability of the unit.

h. Configuration Control.

A "change log" is to be maintained which describes all changes made to the unit during or as a result of testing. Test and data sheet numbers applying to each change are to be recorded in the change log.

1. Comparison Tests.

Whenever permitted to do so by time considerations, run duplicate tests in the BioMarine 60 unit on hand. Duplicate tests should follow the rebreather tests immediately, if possible, to minimize the problems associated with maintaining identical test setups. Use Data Sheets 1, 3, 4, 5, or 6 (Attachment 2) as appropriate.

j. Performance Estimate.

At the conclusion of all tests, an estimate of the rebreather performance is to be made which addresses at least the following areas:

- (1) Duration of gas supply.
- (2) Duration of CO_2 absorbent canister.
- (3) Inspired pO_2 performance as a function of B and RMV.
- (4) Breathing resistance and maintenance of positive facepiece pressures.
- (5) Cooler performance and duration
- (6) Weight.

ATTACHMENT 1 TO APPENDIX D

TEST SETUPS

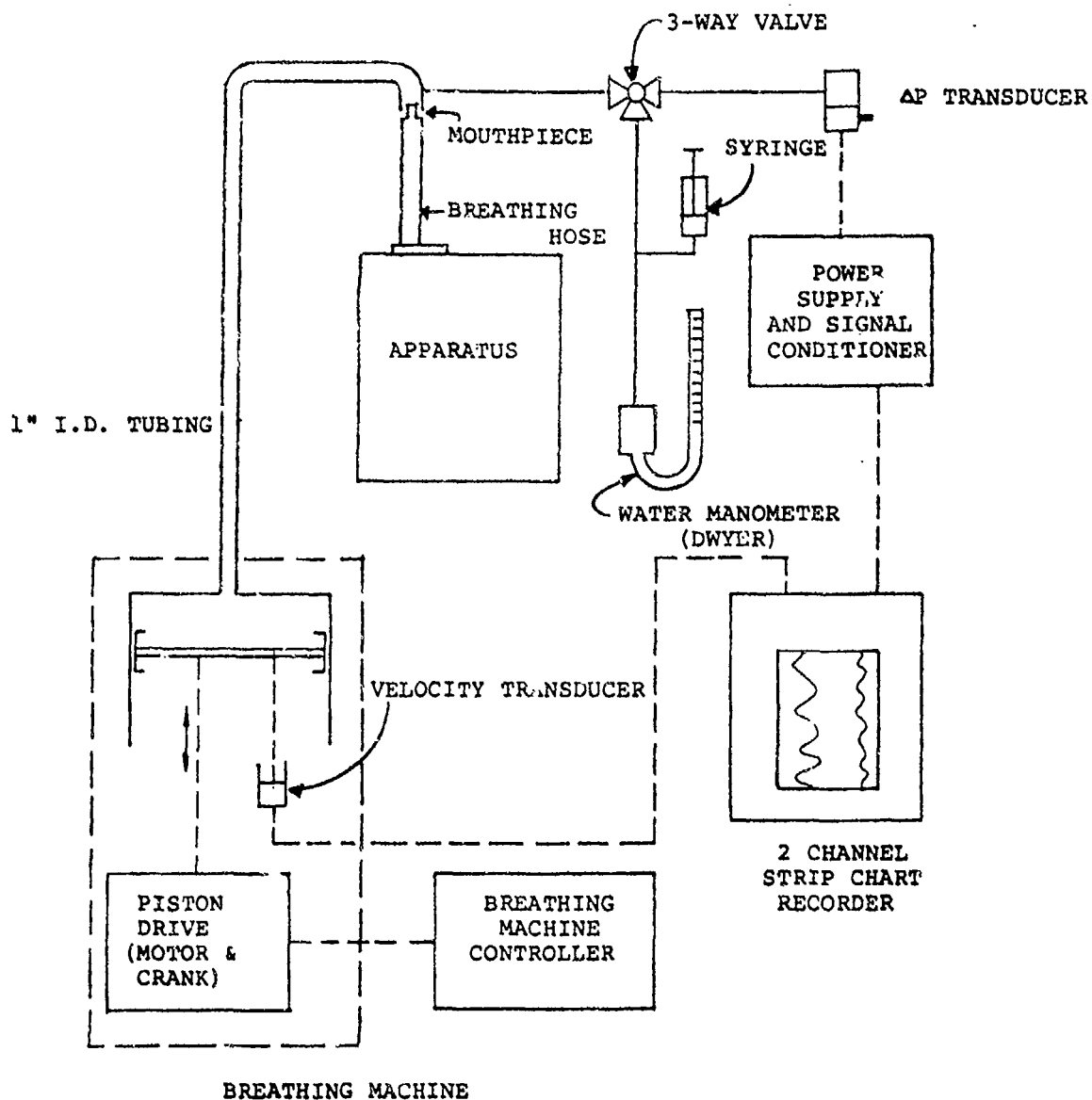


Figure D-1. Breathing Resistance Test Setup.

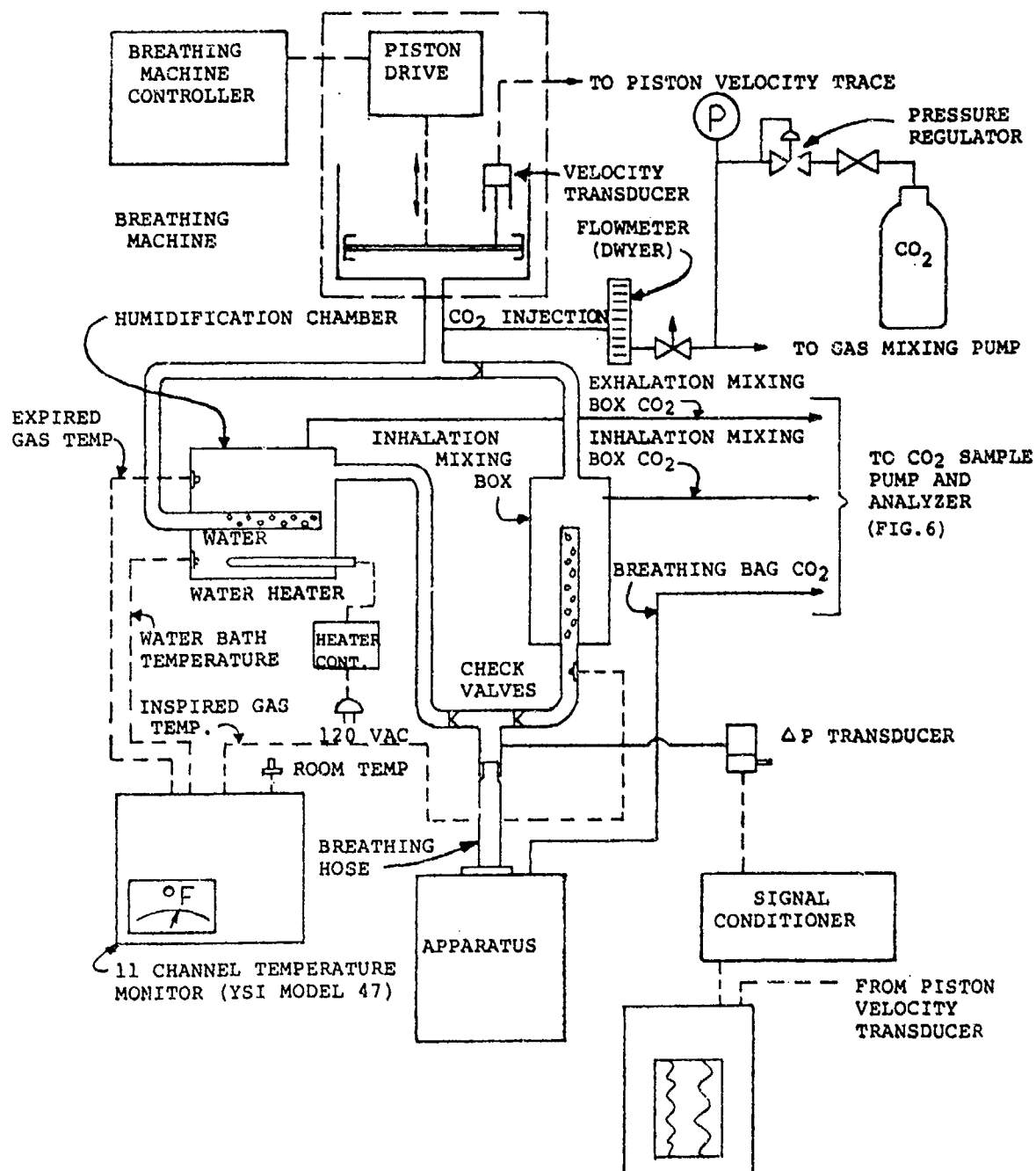


Figure D-2. Inspired Gas CO₂ Test Setup.

ATTACHMENT 2 TO APPENDIX D

TEST SETUPS

ACTUAL VERSUS PREDICTED PRESSURE DROPS

Data Sheet 1

Test No.: _____
 Date: _____
 Recorder: _____

BPM: _____
 TV: _____ liters
 RMV: _____ liters/min
 Peak Flow: _____ lpm

Flow Element	Predicted Maximum ΔP		Actual Maximum ΔP		Ratio	
	inh	exh	inh	exh	inh	exh
1						
2		-				
3		-		-		
4		-		-		
5						
6						
7	-		-			
8	-		-			
9	-		-			
10	-		-			
11	-		-			
12	-		-			
13	-		-			
14	-		-			
15	-		-			
16	-		-			
17		-	-	-		
18		-		-		
19		-		-		
20						

Mouthpiece
 ΔP re ATM
 Pressure

NOTES:

COMPUTER MODEL INPUTS BASED ON MEASURED PERFORMANCE CONFIGURATION

Data Sheet 2

INPUT NO.	FLOW ELEMENT	LIST NO.	<u>ΔP DATA</u>		
			<u>D₁</u>	<u>D₂</u>	<u>D₃</u>
1.	Mouthpiece	1			
2.	Mouthpiece Check Valve	2,8			
3.	Hose To/From Mouthpiece	3,9			
4.	Duct From Main Bellows	4			
5.	Main Bellows Outlet	5			
6.	Bellows Flapper Valve	6,16,17			
7.	Duct To Scrubber	10			
8.	Gas Supply Duct	7			
9.	Scrubber	11			
10.	Duct To Cooler	12			
11.	Duct To Exhaust Bellows	15			
12.	Cooler	13			
13.	Duct To Main Bellows	14			
14.	Exhaust Duct	18			
15.	Exhaust Valve	19			
16.	Duct From Supply Bellows	20			
17.	Bellows Force-Constant	(grams)			
18.	Bellows Spring Rate	(grams/liter bellows volume)			
19.	Bellows Spring Zero Volume	(liters bellows volume)			
20.	Main Bellows Volume-Maximum	(liters)		NA	
21.	Main Bellows Volume-Minimum	(liters)		NA	
22.	Main Bellows End Area	(cm ²)			

COMPUTER MODEL INPUTS BASED ON MEASURED PERFORMANCE
CONFIGURATION _____ (CONCLUDED)

Data Sheet 2

<u>INPUT NO.</u>	<u>FLOW ELEMENT</u>		
23.	Supply/Main Bellows Volume		
24.	Exhaust/Main Bellows Volume		
25.	RMV	(liters/minute)	NA
26.	BPM	(minute ⁻¹)	NA
27.	Constant Flow Rate Total	(liters/minute)	
28.	Supply Demand Valve Setting	(cm H ₂ O below 1 atmos.)	
29.	Initial Main Bellows Volume	(liters)	NA
30.	No. of Increments per Breath - (maximum 200)		NA

Items 1 to 16 in the form $\Delta P \text{ (cm H}_2\text{O)} = D_1 + D_2 \text{ (liters/minute)}^{D_3}$

Test No.: _____

Date: _____

Recorder: _____

FIRST STAGE REGULATOR OUTLET PRESSURE

First Stage Regulator:

Bottle Pressure	RMV ¹ (lpm)	First Stage Outlet Pressure (PSIG)	
		Maximum	Minimum
2000			
1500			
1000			
900			
700			
600			
500			
400			
350			
300			
250			
200			

Notes:

1. 3.0 1 TV

Test No. _____

Date _____

Recorder _____

Data Sheet 4

BPM	TV (l)	RMV (l/m)	Time		Bottle Press.		Flows							Design Flow
			(min:sec)	(breaths)	Start fsw	Stop fsw	Spirometer		Bottle			Min. Safe (l/m) ②	Level ①	
							(l)	(l/m)	(l)	(l/m)	(l/m)			

Rebreather Configuration:

	<u>displacement (l/inch)</u>	<u>compliance</u>
Main bellows	_____ cm ³	from +1.0 to +3.0 inch H ₂ O
Supply bellows	_____ cm ³	from -2.5 to +0.5 inch H ₂ O
Exhaust bellows	_____ cm ³	from +2.0 to +1.0 inch H ₂ O
Exhaust Sample pump on _____	off _____	

- Notes: 1. Note if main bellows is "bottoming out" (B) or "topping out" (T)
2. Based on exhaust $pO_2 = 0.18$ atm, supply gas = 60% O_2 , $B = 0.035$, $RMV \leq 30$ $B = 0.05$, $RMV > 30$ lpm
3. Nominal value here is the steady state flow rate, F , nominally 1.0 lpm
- Note: First Stage Outlet Pressure = _____ psig

Data Sheet 5

BPM	TV (l)	RMV (l/m)	Time	CO ₂ Removal Actual Setting	Ⓐ Removal Rate (slpm)		Bottle Press.		Flows								Exhaust Flow Split Exh/Inh
			Start fsw				Stop fsw	Spirometer		Bottle		Ⓐ + Ⓑ (l/m)	Min. Safe (l/m) Ⓓ	Level Ⓔ			
								(l)	(l/m)	(l)	(l/m)						
			(min:sec)								Ⓑ						

Rebreather Configuration:

displacement (l/inch)

compliance

Main bellows _____ cm³ from +1.0 to +3.0 inch H₂O
 Supply bellows _____ cm³ from -2.5 to +0.5 inch H₂O
 Exhaust bellows _____ cm³ from +2.0 to +1.0 inch H₂O
 Exhaust Sample pump on _____ off _____

- Notes: 1. Note if main bellows is "bottoming out" (B) or "topping out" (T)
 2. Based on exhausted pO₂ = 0.18 atm, supply gas = 60% O₂, R = 0.055, RMV = 30; R = 0.04, RMV = 30 lpm
 3. Nominal value here is the steady state flow rate, V, nominally 1.0 lpm
 Note: First State Outlet Pressure = _____ psig

Data Sheet 6

BPM	TV (1)	RMV (l/m)	B	O ₂ (Z)				O ₂ Uptake (slpm)		CO ₂ Add (slpm) 20 psi Meter	O ₂ ② ③ Add Rate (slpm)	Pred pO ₂ insp. (Z)	Supply psi/time (min)	Supply Flow (slpm)
				Supply Gas	Inh Mix Box	Exh Mix Box	Main Bellows	Design ③ ①	Actual ③					

- Notes: 1. Design O₂ Uptake Rate (slpm) = B x RMV
2. O₂ add rate = average supply gas flow (slpm) from Data Sheet 4 x Supply Gas % O₂
3. $slpm = slpm \times \left(\frac{471 \cdot R}{P + 440} \right) = \left(\frac{P_{atm}}{29.92 \text{ in Hg}} \right)$